

A Comparative Study On The Physical Properties of Natural Sedimentary Loess And Manual Filling Compacted Loess

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Abstract

With the development of human society, mega engineering projects of removing the tops of hills to infill valleys began to appear in the loess region. The thickness of the manual filling compacted loess can reach tens of meters. For such large-scale construction projects, studying the properties of compacted loess is essential to ensure the safety and reliability of land creation and artificial infrastructure. In this paper, the specimens from two exploration well profiles were carried out to study the physical properties of natural loess and compacted loess from the Loess Plateau. Here the natural loess selected was deposited in old ages (Q_2 and Q_1) and had strong stability. The natural water content, dry density, specific gravity, liquid limit, plastic limit, plasticity index, clay fraction, silt fraction, sand fraction, compression modulus, and permeability coefficient have been determined. Statistical theories such as t-test and correlation coefficient checks were used to describe the difference between the two kinds of loess, and the degree of correlation among various indicators. Besides, 14 groups of exploration well data in 8 studies were collected. The variation of natural water content and dry density with well depth was analyzed to supplement the existing data. Results have shown that the manual filling compacted loess is significantly different from the natural loess. On the whole, the liquid limit, plastic limit, plasticity index, clay fraction, silt fraction, sand fraction and compression modulus of the compacted loess are smaller. And compared with the natural sedimentary loess with strong stability, it deforms more easily. The difference of compression modulus between the compacted loess and natural loess is mainly controlled by the dry density and the particle composition. Moreover, the heterogeneous level of the manual filling compacted loess is greater than that of the natural loess in the horizontal direction and smaller than that of the natural loess in the vertical direction. Under a combination of external hydrologic conditions and dead weight, the compacted loess will become more stable.

Introduction

Loess is a predominantly silt-sized Quaternary sediment which has a wide distribution in arid and semi-arid regions (Peng et al., 2018). It covers approximately 10% of the Earth's land surface, and can be found over large areas of Eurasia, South and North America, and smaller areas of New Zealand, Australia, Africa, and the Middle East (Muhs et al., 2014). In China, the total area of loess and loess like soils is approximately 630,000 km², being about 6.3% of the country's land surface (Lin and Liang, 1980). Due to its special properties of high water sensitivity and collapsibility (Gao, 1988; Leng et al., 2018), loess is prone to uneven deformation under the action of external forces and water, which has caused many problems in infrastructure construction in the loess area (Grabowska-Olszewska, 1988; Lin and Wang, 1988; Sadeghi et al., 2019; Smalley, 1992; Zang et al., 2019). How to eliminate the collapsibility and ensure the stability of the projects has aroused extensive research in past decades (Evstatiev, 1988; Feng et al., 2015; Gaaver, 2012; RenéJacques, 1988; Tan, 1988).

According to Evstatiev (1988), the loess improvement methods have been classified into 8 groups, including compaction, the addition of coarser materials, injection of various adhesives, various cushions or jet grouting, geomembranes, etc. Based on the statistics provided by the Soviet Union, compaction is the most cost-effective way to improve loess. Its basic principle is to increase the density of loess by rolling or heavy tamping. As early as the 1930s, the Soviets firstly used compaction to improve the loess foundations (Abelev, 1939). Since World War II, it has been used in almost all countries for engineering construction on loess soils (Evstatiev, 1995; Fonte et al., 2018; Gao et al., 2004; Houston et al., 2001). The scale of these projects was generally not large, only involving a small amount of building foundations in most cases, and the thickness of compacted loess was generally no more than 10 meters. As a consequence, it was unlikely to cause widespread changes to the surrounding terrain.

However, with the continuous development of human society, some new projects begin to appear. Loess Plateau, the most concentrated and largest loess area on the earth, spans seven provinces in China, making up 20% of arable land and supporting 17% of its population (Zhang, 1993). Due to serious soil erosion and shortage of urban land, in recent years, local governments have promoted projects that remove the tops of mountains to fill in valleys to create lands for developments (Li et al., 2014). The project, called mountain bulldozing and city creation (MBCC), has become the largest loess project in the world. Dozens of hills 100–150 meters in height were being flattened over hundreds of kilometers, and the height of compacted loess filled in the gully could exceed 80 meters. Given the scale of such mega-projects, there is no experience to draw from. Whether this large-scale manual filling compacted loess can be kept stable for a long time to meet the urban construction demand needs to be studied urgently.

Different from previous projects, there is not only manual filling compacted loess but also natural sedimentary loess in the MBCC projects, which formed two types of sites, namely filled area and excavated area. Recent work by engineers has established that the foundations of the two areas have obvious differences (Ge et al., 2017; Zhang et al., 2019). In the excavated area, the natural sedimentary loess is uniform in nature and has good engineering geological conditions. By contrast, due to the differences in filled thickness, soil quality, tamping quality, and moisture content, the manual compacted loess in the filled area has a different degree of compressibility and collapsibility. These differences make the foundation in the filled area prone to uneven settlements, and ground fissure often occurs at the contact place of the excavated area and filled area. Hence, the comparative study of these two kinds of loess is of great value to the stability analysis of the site. Moreover, in the

current evaluation system, the engineering quality of the filled body is mainly achieved by controlling the compaction degree and dry density of the loess after layered compaction (Wu, 2018). However, the backfill compacted loess is formed by human reconstruction in a short period, and it will take a long time to stabilize under the influence of various factors such as the change of external water environment and overburden pressure (Kong et al., 2018). Therefore, the stratified and batch detection results in the construction stage do not necessarily represent the overall pressure and change of the filled body (Zhang et al., 2019). As the basic physical properties of the backfill compacted loess directly reflect the construction quality and its strength and deformation characteristics are directly related to the long-term stability of the high filled body, the physical and mechanical properties of the backfill compacted loess after construction remain a major problem to be investigated.

For several decades, a large number of scholars have carried out research on the properties of natural and compacted loess from both micro macro scales. It has previously been observed that the compacted loess is quite different from the natural loess (Jiang et al., 2014; Ng et al., 2016; Sadeghi et al., 2016; Zhang et al., 2020). Even though the dry density of compacted loess is the same as that of natural loess, their micro-structure is still quite different (Rendell, 1988; Wang et al., 2018). Moreover, the compacted loess can still have water sensitivity and collapsibility, which can be even more serious than the natural loess (Chen and Sha, 2009; Jia, 2000; Ma et al., 2017; Wu et al., 1997; Zhang, 1986). Besides, several attempts have been made on the relationship between the physical and mechanical properties of compacted loess. Wang et al. (2006) studied the water diffusion ratio of unsaturated compacted loess considering the influence of density, and the results have shown that the permeability coefficient of the unsaturated dense loess is sensitive to soil density change compared with loose loess. When the dry density is unchanged, the cohesion and internal friction angle slightly decrease as the water content increases. Based on one-dimensional consolidation tests, Chen and Sha (2010) discussed the relationship between physical indices (water content, compaction degree) and deformation indices (compression deformation coefficient, compression coefficient) of the compacted loess. They have found that the compression deformation coefficient and compression coefficient increased with the increase of water content, and decreased with the increase of compaction degree. Kim and Kang (2013) investigated the mechanical characteristics of four kinds of compacted loess having different clay contents (10%, 20%, 25%, and 30%), and implies that the resilient behavior of compacted loess materials was considerably affected by the clay content. Li et al. (2019) used Mercury intrusion porosimetry (MIP), scanning electronic method (SEM), and filter paper method to explore the pore size distribution (PSD), the soil water characteristics (SWCC), and the microstructure of the compacted loess at different water contents. It is found that the moisture content can significantly affect the microstructure and soil water characteristics of compacted loess.

However, previous studies have mainly focused on the compacted loess manufactured under laboratory conditions, and the selection of physical indicators is sole and disperse, so that the test results may not accord with the laws of loess on site. More recently, because of the MBCC project, literature has emerged that offers data about the manual filling compacted loess in large-scale high-fill sites (Duan et al., 2018; Ge et al., 2017; Kong et al., 2018; Yin et al., 2016). Nonetheless, existing researches mainly focus on the monitoring parameters like soil moisture content, pore water pressure, and settlement, lacking systematic analysis of other physical and mechanical parameters. What's more, there have been no controlled studies which compare differences in the layers at different depth of the natural and compacted loess.

In this paper, comprehensive comparison and analysis of the physical properties were carried out to study the exploration well profiles of natural loess and compacted loess from the Loess Plateau. The data were partly from experiments and partly from the previously published literature. Statistical theories such as t-test and correlation coefficient checks were used to describe the difference between the two kinds of loess, and the degree of correlation among various indicators.

This study has complemented the current research data on MBCC projects which is helpful for further understanding the environment changing in large-scale compaction loess projects, and has important practical significance to ensure the safety and reliability of land creation or man-made infrastructures. In addition, it has provided a new idea to describe the difference and correlation of physical indices of loess.

Methodology

Soil sampling

The samples of loess used in this study were obtained from a site of MBCC projects in Yan'an City, Shannxi, China (Fig. 1). The site is located in the southeast of the downtown area and the construction was completed in November 2017. The filling area was compacted by layer rolling and tamping, and the filling and excavation joint was compacted by dynamic compaction. Besides, a supplementary dynamic compaction was carried out on the filling body after approximately every 5 meters of filling.

In order to obtain natural loess and compacted loess samples, two exploration wells were excavated. One (well A) was located in the filling area, which was the center of the gully before construction and the fill height was about 40 meters, and the other (well B) was located in the excavation area, which was loess ridge before construction and the excavation height of the hill was approximately 12 meters. The depth of

well A was 25m and the depth of well B was 29m. Neither well reached the water table. The horizontal distance between the two wellheads was about 600 meters and the elevation difference was about 70 meters. Given the openness and flatness of the site, the two wells were in the same climate essentially.

In the Loess Plateau of China, a typical profile of loess-paleosol sequences consists of Wucheng loess (Q1), Lishi loess (Q2), and Malan loess (Q3) from the bottom up (Li et al., 2018). According to the study of loess strata and loess distribution by Liu (1985), Wucheng loess (Q1), Lishi loess (Q2), and Malan loess (Q3) all exist in Yan'an City. By on-site investigation and collection of engineering data, the natural loess samples from well A were Lishi loess (Q2) and Wucheng loess (Q1), while the manual filling compacted loess samples were the mixture of a little Malan loess (Q3) and Lishi loess (Q2).

The natural and compacted loess samples were taken from the exploration wells at intervals of 1 m and carefully collected at well wall depths of more than 10 cm to reduce the influence of the well excavation process on the samples. Due to the difficulty of sampling under the depth of 20m in well B, the natural block samples in the deep layers were taken at intervals of 2m.

At the sampling site, the block loess samples were cut into cylinders with a diameter of 12cm and a height of 20cm, and were well sealed by soil samplers, plastic wrap, and plastic tapes to avoid disturbance during the transportation to the laboratory. Then the block samples were made indoors into needed specimens for various geotechnical characterization tests. To ensure the representativeness of the specimens, the loose soil specimen is a mixture of several cylinder samples from the same layer.

Soil tests

The soil indices measured or calculated in the geotechnical tests are of clear physical significance. These soil indices can be classified into various types such as physics, hydrology, and mechanics, which reflect the properties of loess such as its material composition, structural characteristics, and current occurrence state. In this study, a large number of soil tests were conducted on the natural and compacted loess specimens collected from the site, in order to characterize their basic physical properties from vertical profiles. The indices obtained through the tests include natural water content, dry density, specific gravity, liquid limit, plastic limit, plasticity index, clay fraction, silt fraction, sand fraction, compression modulus, and permeability coefficient (Table 1). All the test processes referred to the two national specifications in China, Standard for *Soil Test Method* (PRC-MOHURD, 1999) and *Test Methods of Soils for Highway Engineering* (RPC-MOT, 2007). Here the specimens for the tests to get the natural water content, specific gravity, liquid limit, plastic limit, plasticity index, clay fraction, silt fraction and sand fraction are loose soil. And the others are blocky specimens. A brief description of these procedures is given below.

The wet density, natural water content, and specific gravity are so-called basic index properties of soil. Part of the specimens was weighed in situ and then taken back to the laboratory for drying in an oven. By measuring the mass of water and the mass of dry soil, the natural water content (w) was obtained.

Through the mental ring method, it could be easy to get the weight of the specimen of fixed volume, so that the wet density (ρ) of the specimens could be calculated. The dry density (ρ_d) could be obtained by the following formula. For specimens from each layer, multiple tests were carried out, and the resulting ρ_d was the average of all test results to make sure that the results were representative.

$$\rho_d = \frac{\rho}{1+w} \quad (1)$$

The specific gravity (G_s) is the ratio of the constant weight of the dried soil particles to the mass of pure water at 4°C at the same volume. In this study, G_s was measured using the pycnometers and the solid particles were fully dispersed in water by vacuum extraction instead of water bath heating.

The liquid limit (LL), plastic limit (PL), and plasticity index (I_p) are the indices to reflect the consistency and plasticity behavior of soil and generally correlated with the water content. LL is the limit water content between the plastic state and flowing state of clayed soil, and PL is the limit water content between the plastic state and semi-solid state (Fig. 2). The difference between the liquid limit and the plastic limit is I_p .

In this study, these indices were derived by the liquid–plastic limit combined determination method. Approximately 200 grams of representative specimens were well mixed with a certain amount of distilled water and carefully put into a sample cup. The surface was flat and smooth. Then the sample cup was placed at a suitable height and a cone was dropped into the sample. The depths at which the cone penetrated the sample and the moisture contents of the sample near the cone tip were all measured. All the steps were repeated at least three times to get different water content. For semi-solid, plastic, and flowing states, the depths should be 3–4 mm, 7–9 mm, and 15–17 mm. After that, a best-fit curve defining the relationship between the water content and the depth of penetration could be drawn in a double-logarithm coordinate system. Here the LL was the water content at which the cone penetration depth was 17 mm and the PL was the water content at which the cone penetration depth was 2 mm.

The particle size distributions were obtained from a Malvern Mastersizer3000 laser analyzer at the Institute of Geology and Geophysics, Chinese Academy of Sciences. And it should be noted that the dispersant agent (sodium hexametaphosphate) was added to the soil-water mixture before the test to avoid the flocculation of fine particles. According to Shirazi and Boersma (1984), the particles can be divided into three categories: clay(< 2 μ m), silt(2–50 μ m), and sand(> 50 μ m). So that there were three other indices, the clay fraction (N_{cl}), the silt fraction (N_{si}), and the sand fraction (N_{sa}).

The consolidation test is a kind of compression test to determine the pressure of clay samples under the condition of lateral limits. The specimen was placed in a vessel with lateral limits and axial drainage permits, and the pressure was gradually increased to determine the relationship between the pressure and the specimen's deformation or pore ratio, and the relationship between deformation and time. In this study, the initial water content of the specimen was its natural water content, and the graded loading pressures used in the test were 50kPa, 100kPa, 150kPa, 200kPa, 400kPa, 800kPa, 1200kPa, 1600kPa, respectively. The compression modulus (E_s) is defined as the ratio between the vertical stress increment of soil and the corresponding strain increment under the condition of complete lateral limits. Here, the E_s corresponding to the pressure interval of 100kPa to 200kPa was adopted.

The permeability coefficient (k) was measured by the device shown in Fig. 3. The samples were cut into cylindrical specimens with a diameter of 61.8mm and a height of 40mm and then the specimen was put into the permeable container to be saturated with water. Control the outlet water pressure to 10–20 kPa, and then measure the water output within a certain period. The same specimen was measured for no less than three times with different water pressure to ensure the accuracy of the measurements. The average of the ratio of water output to corresponding time obtained from multiple measurements was the k used in this study.

Table 1
The physical indices and their symbols.

Item	Symbol	Unit
natural water content	w	%
dry density	ρ_d	g/cm ³
specific gravity	G_s	/
liquid limit	LL	%
plastic limit	PL	%
plasticity index	I_p	%
clay fraction	N_{cl}	%
silt fraction	N_{si}	%
sand fraction	N_{sa}	%
compression modulus	E_s	MPa
permeability coefficient	k	cm/s

Data collection

Due to the difficulty, time consuming and high price of sampling in exploration wells, only two wells were excavated in this study and the amount of data acquired was limited. As a complement, 14 groups of exploration well data in 8 studies were collected from previously published literature. Table 2 has shown the basic information of these data. There are 8 groups of data about the natural sedimentary loess and 6 groups of data about the manual filling compacted loess. Here the data of compacted-ya5# were from the newly completed site. And three groups of data, compacted-lz1#, compacted-lz2#, and compacted-lz3#, were derived from monitoring equipment installed in exploration wells, while the other groups of data were obtained by conducting tests on block samples taken from the exploration wells. It should be emphasized that, due to the limitations of previous research parameters, the collected data in this paper only included natural water content (w) and dry density (ρ_d).

Statistical analysis

The data obtained from the tests were sorted out in Excel according to the sampling depth and the loess type (natural or compacted). The differences of w , ρ_d , LL , PL , I_p , N_{cl} , N_{si} , N_{sa} , G_s , E_s , and k in different soil layers between the natural loess and the compacted loess were analyzed in the broken line graphs. Then the statistical analysis of all the indices was carried out with the Statistical Product and Service

Solutions (SPSS). Here the mean–standard deviation (SD) and independent-samples t-test were used to determine whether there were significant differences between the natural loess and the compacted loess. The data sets were divided into the following groups: all samples, samples with a dry density less than 1.6 g/cm³, samples with a dry density greater than 1.6 g/cm³ and less than 1.7 g/cm³, and samples with a dry density greater than 1.7 g/cm³. And based on the dataset that included all samples, the spearman's rank correlation coefficients between every two indices of the same kind of loess were obtained. A P-value < 0.05 was considered as significant, and a P-value < 0.01 was considered as highly significant (Trujillo-ortiz et al., 2004).

Table 2
The basic information of the collected data.

Type	Group ID	Reference	Sampling site	Well depth (m)	Data points	water content (w)	dry density (ρ_d)
natural sedimentary	natural-wb1#	He and Zhou (2020)	Shaanxi, Weibei	28	7	√	√
loess	natural-l2#	Li and Li (2007)	Gansu, Zhengning	10	6	√	×
	natural-l3#		Gansu, Xifeng	16	14	√	×
	natural-l4#		Gansu, Zhenyuan	14	12	√	×
	natural-l5#		Gansu, Qingyang	20	17	√	×
	natural-l6#		Zhou et al. (2018)	Qinghai, Gushan	25	25	√
	natural-l7#	Qinghai, Gushan		20	20	√	×
	natural-l8#	Mei (2013)	Shanxi, Lvliang	10	10	×	√
	manual filling compacted loess	compacted-lz1#	Duan et al. (2018)	Gansu, Lanzhou	33	7	√
compacted-lz2#		Gansu, Lanzhou		22	5	√	×
compacted-lz3#		Gansu, Lanzhou		15	3	√	×
compacted-ya4#		Yin et al. (2016)	Shaanxi, Yanan	33	33	√	√
compacted-ya5#		Wu (2018)	Shaanxi, Yanan	40	4	√	√
compacted-l16#		Mei (2013)	Shanxi, Lvliang	5	5	×	√

Results

Variation of the indices with well depth

Results from the experimental data

The variation of all the indices with well depth for the natural and compacted loess obtained from experiments is shown in the following figures (Figs. 4–7). It should be emphasized that some data were not obtained due to the lack of specimens and the failure of experiments, such as the dry density, compression modulus and permeability coefficient of the natural loess specimens at the depth of 1m and 2m. Such results are not listed in the figures.

The variation with well depth of basic index properties, including natural water content, dry density, and specific gravity, is shown in Fig. 4.

It can be easy to find that the variation range of natural water content of the natural loess is larger than that of the compacted loess (Fig. 4a). The natural water content of the compacted loess specimens is concentrated between 10.0% and 16.0%, while that of the natural loess specimens is between 5.0% and 20.0%. In the depth range of 0 ~ 5m, the difference of natural water content between two kinds of loess is not

obvious, except the natural water content of the compacted loess with a depth of 2m. At the depth of 6m, the natural water content of the natural loess decreases to nearly 5%. And in the depth range of 5 ~ 15m, the natural water content of the compacted loess is obviously greater than that of the natural loess. However, it is completely opposite after the depth exceeds 15m. Moreover, the natural water content of the natural loess shows an increasing trend after the depth exceeds 6m, but such rule in the compacted loess begins after the depth exceeds 15m.

From Fig. 4b, one can find that the dry density of the natural loess increases with the increasing depth. Except for the dry densities at the depth of 2m and 10m, the dry density of the compacted loess also shows a slight upward trend with depth. In the depth range of 0 ~ 20m, the dry density of the compacted loess fluctuates more widely than that of the natural loess, as the dry density of the natural loess specimens is concentrated between $1.5\text{g}/\text{cm}^3$ and $1.7\text{g}/\text{cm}^3$, while that of the compacted loess specimens is between $1.4\text{g}/\text{cm}^3$ and $1.9\text{g}/\text{cm}^3$. The length of the error bar indicates the standard deviation of dry density of the specimens in the same layer. And it can be easy to find that the standard deviation of the dry density of the compacted loess is much higher than of the natural loess.

The variation of specific gravity of the two kinds of loess with well depth is shown in Fig. 4c. It is shown that the specific gravity range of the natural loess and the compacted loess is basically the same. The variation range is from 2.67 ~ 2.72, approximately.

The plasticity is one of the states of consistency of the soils, which means the ability to keep a deformation without breaking. Figure 5 shows the variation of three kinds of plasticity indicators with well depth. It is obvious that the liquid limit, plastic limit, and plasticity index of the natural loess are generally greater than that of the compacted loess. For the compacted loess, the liquid limit is concentrated between 28.0% and 32.0%, the plastic limit is concentrated between 16.0% and 18.5%, and the plasticity index is concentrated between 11.0% and 15.0%. For the natural loess, the liquid limit is concentrated between 30.0% and 34.0%, the plastic limit is concentrated between 17.0% and 19.5%, and the plasticity index is concentrated between 12.0% and 16.0%. In particular, the liquid limit, plastic limit, and plasticity index of the natural loess increase significantly when the depth exceeds 25m.

Soil particle is an important part of its structure and the percentage of soil fractions can directly affect other physical properties. From Fig. 6, it can be easy to find that the proportion of the silt particles is the largest, both for the compacted loess and for the natural loess. The second-largest proportion is the sand particles and the third one is the clay particles, without considering the results of the natural loess at the depth of more than 25m. And the variation range of the clay fraction is smaller than that of the silt fraction and the sand fraction. Figure 6a also shows that the variation range of clay fraction of the natural loess is larger than that of the compacted loess. And for the natural loess, the clay fraction shows an increasing trend after the depth exceeds 6m.

Besides, in the depth range of 0 ~ 5m, the clay fraction and silt fraction of the natural loess are slightly larger than those of the compacted loess, except the results of the compacted loess with a depth of 2m. And in the depth range of 5 ~ 15m, the clay fraction and silt fraction of the natural loess are slightly smaller than those of the compacted loess. After the depth exceeds 15m, the clay fraction and silt fraction of the natural loess become obviously greater than the compacted loess again. While the variation rule is completely opposite for the sand fraction.

The variation of compression modulus with well depth is shown in Fig. 7a. The compression modulus of the compacted loess specimens is concentrated between 15MPa and 45MPa, while that of the natural loess specimens is between 30MPa and 70MPa. On the whole, the compression modulus of the natural loess is greater than that of the compacted loess.

The variation of permeability coefficient with well depth is shown in Fig. 7b. It can be easy to find that the permeability coefficient of the natural loess and the compacted loess tends to decrease with the increasing depth. And this trend is more obvious in natural loess. In the depth range of 6 ~ 9m, the permeability coefficient of the natural loess is larger than that of the compacted loess. After the depth exceeds 17m, the permeability coefficient of the natural loess is smaller than that of the compacted loess.

Results from the collected data

The variation of natural water content and dry density with sampling depth obtained from data collection is shown in Fig. 8 and Fig. 9. The experimental data are also shown in the figures for comparison.

With the exception of the three groups of data from monitoring equipment, the natural water content of the compacted loess is concentrated between 9.0% and 18.0% (Fig. 8a), while that of the natural loess is between 5.0% and 25.0% (Fig. 8b). Although the data came from different regions, in the depth range of 0 ~ 5m and more than 20m, the difference of natural water content between different groups is not obvious, both for compacted loess and for natural loess. However, in the depth range of 5 ~ 15m, the natural water content of natural loess varies greatly from group to group, while the same scene has not played out in compacted loess. In the depth range of 0 ~ 5m, the natural water content of either compacted loess or natural loess is basically concentrated in 10.0 ~ 20.0%. Considering all the data, when the depth exceeds 15m, the natural water content of the natural loess is obviously greater than that of the compacted loess, and we can also find that there is an increasing trend of the natural water content for the natural loess in this depth range, however, the same trend doesn't present in compacted loess.

From Fig. 9, one can find that the dry density of both natural loess and compacted loess would increase with the depth increasing, and this variation trend is more apparent in natural loess. For compacted loess, the dry density of the specimens in the depth range of 0 ~ 15m fluctuates more widely than that of the specimens with a depth exceeded 15 m (Fig. 9a). In addition, although the data of compacted loess, compacted loess-ya4# and compacted loess-ya5# were from the same region, the dry density varies greatly. By contrast, even from different regions, the difference of the dry density between different groups of natural loess is not so obvious (Fig. 9b).

Statistical result

Results from the mean–standard deviation (SD) and independent-samples t-test

For the dataset of all samples, the results obtained from the mean–standard deviation (SD) and independent-samples t-tests of the indices are presented in Table 3. According to Fisher's Exact Probability Test (Trujillo-ortiz et al., 2004), there are significant differences in the silt fraction, sand fraction and compression modulus between the natural and compacted loess, and there are highly significant differences in the ρ_d - D (the standard deviation of loess dry density per layer), liquid limit, plastic limit, plasticity index and clay fraction between the natural and compacted loess.

Furthermore, considering the mean values, the ρ_d - D and sand fraction of the compacted loess are significantly larger than that of the natural loess. The liquid limit, plastic limit, plasticity index, clay fraction, silt fraction and compression modulus of the compacted loess are significantly smaller than that of the natural loess.

The standard deviation can reflect the dispersion of a data set. Considering all the specimens at different burial depths, it can be easy to find that the liquid limit, plastic limit, plasticity index, clay fraction, silt fraction, sand fraction and compression modulus of the compacted loess are more uniform than those of the natural loess. While the natural loess has more uniform ρ_d - D .

Table 3 The mean– standard deviation (SD) and independent-samples t-tests results of all samples.

The indices	Compacted loess	Natural loess	p-value
w	13.633 ± 1.825	13.682 ± 4.142	0.954
ρ_d	1.666 ± 0.115	1.635 ± 0.083	0.283
ρ_d - D	0.038 ± 0.039	0.011 ± 0.011	0.003
G_s	2.696 ± 0.015	2.700 ± 0.014	0.341
LL	30.375 ± 1.246	33.124 ± 2.630	0.000
PL	17.463 ± 0.829	18.468 ± 0.953	0.000
Ip	12.912 ± 1.170	14.656 ± 2.367	0.002
N_{cl}	3.804 ± 0.535	4.616 ± 1.332	0.008
N_{si}	77.645 ± 3.897	80.542 ± 4.810	0.024
N_{sa}	18.550 ± 4.285	14.840 ± 5.863	0.014
E_s	31.846 ± 13.143	49.524 ± 27.149	0.011
k	1.63E-05 ± 3.11E-05	1.63E-05 ± 2.64E-05	0.997
ρ_d - D means the standard deviation of loess dry density per layer;			

All values are given as mean ± standard deviation;

p-value < 0.05, indicating statistical significance;

p-value < 0.01, indicating highly statistical significance.

Table 4 The mean– standard deviation (SD) and independent-samples t-tests results of samples with a dry density less than 1.6 g/cm³.

The indices	Compacted loess	Natural loess	p-value
<i>Well depth</i>	8.170 ± 4.622	9.900 ± 4.977	0.500
<i>w</i>	13.371 ± 2.143	10.415 ± 3.070	0.058
ρ_d	1.510 ± 0.052	1.565 ± 0.023	0.048
$\rho_d D$	0.037 ± 0.020	0.016 ± 0.014	0.024
<i>G_s</i>	2.694 ± 0.014	2.697 ± 0.014	0.790
<i>LL</i>	30.119 ± 0.725	31.895 ± 0.991	0.002
<i>PL</i>	17.100 ± 0.749	18.818 ± 0.767	0.001
<i>l_p</i>	13.019 ± 0.594	13.078 ± 0.802	0.879
<i>N_{cl}</i>	3.728 ± 0.341	3.939 ± 0.893	0.516
<i>N_{si}</i>	77.269 ± 4.771	78.591 ± 4.635	0.596
<i>N_{sa}</i>	19.001 ± 5.055	17.480 ± 5.444	0.588
<i>E_s</i>	17.968 ± 9.308	45.229 ± 21.458	0.011
<i>k</i>	3.70E-05 ± 5.42E-05	2.20E-05 ± 1.90E-05	0.432
$\rho_d D$ means the standard deviation of loess dry density per layer;			

All values are given as mean ± standard deviation;

p-value < 0.05, indicating statistical significance;

p-value < 0.01, indicating highly statistical significance.

Table 5 The mean– standard deviation (SD) and independent-samples t-tests results of samples with a dry density greater than 1.6 g/cm³ and less than 1.7 g/cm³.

The indices	Compacted loess	Natural loess	p-value
<i>Well depth</i>	11.750 ± 7.960	13.500 ± 5.398	0.615
<i>w</i>	13.233 ± 1.796	12.765 ± 3.144	0.720
ρ_d	1.640 ± 0.035	1.641 ± 0.029	0.962
$\rho_d D$	0.406 ± 0.039	0.008 ± 0.008	0.049
<i>G_s</i>	2.702 ± 0.019	2.701 ± 0.016	0.962
<i>LL</i>	30.093 ± 1.539	33.139 ± 1.142	0.001
<i>PL</i>	17.642 ± 0.906	18.001 ± 0.774	0.407
<i>l_p</i>	12.451 ± 1.580	15.137 ± 1.477	0.003
<i>N_{cl}</i>	3.624 ± 0.538	4.526 ± 1.107	0.064
<i>N_{si}</i>	77.138 ± 4.570	80.934 ± 6.018	0.177
<i>N_{sa}</i>	19.239 ± 4.948	14.538 ± 6.893	0.139
<i>E_s</i>	42.394 ± 12.990	61.233 ± 42.441	0.336
<i>k</i>	1.36E-05 ± 2.01E-05	2.09E-05 ± 3.92E-05	0.648
$\rho_d D$ means the standard deviation of loess dry density per layer;			

All values are given as mean ± standard deviation;

p-value < 0.05, indicating statistical significance;

p-value < 0.01, indicating highly statistical significance.

Table 6 The mean– standard deviation (SD) and independent-samples t-tests results of samples with a dry density greater than 1.7 g/cm³.

The indices	Compacted loess	Natural loess	p-value
<i>Well depth</i>	16.550 ± 6.773	25.000 ± 2.739	0.259
<i>w</i>	14.067 ± 1.751	18.339 ± 1.366	0.003
ρ_d	1.771 ± 0.050	1.764 ± 0.043	0.797
ρ_d-D	0.036 ± 0.049	0.008 ± 0.009	0.214
<i>G_s</i>	2.692 ± 0.013	2.703 ± 0.014	0.117
<i>LL</i>	30.721 ± 1.253	34.862 ± 4.317	0.044
<i>PL</i>	17.532 ± 0.827	18.503 ± 1.246	0.063
<i>Ip</i>	13.189 ± 1.049	16.359 ± 3.326	0.046
<i>N_{cl}</i>	3.976 ± 0.604	5.688 ± 1.537	0.025
<i>N_{si}</i>	78.220 ± 3.130	82.899 ± 2.230	0.003
<i>N_{sa}</i>	17.804 ± 3.612	11.414 ± 3.493	0.002
<i>E_s</i>	31.744 ± 6.969	44.063 ± 10.433	0.014
<i>k</i>	7.08E-06 ± 1.46E-05	6.69E-07 ± 1.31E-06	0.307
ρ_d-D means the standard deviation of loess dry density per layer;			

All values are given as mean ± standard deviation;

p-value < 0.05, indicating statistical significance;

p-value < 0.01, indicating highly statistical significance.

Interestingly, when all the indicators are divided into three groups according to the sample's dry density, the independent-samples t-tests results are different. For the samples with a dry density less than 1.6 g/cm³, there are significant differences in the dry density, ρ_d-D and compression modulus between the natural and compacted loess, and there are highly significant differences in the liquid limit, plastic limit between the natural and compacted loess (Table 4). For the samples with a dry density greater than 1.6 g/cm³ and less than 1.7 g/cm³, there are significant differences in the ρ_d-D between the natural and compacted loess, and there are highly significant differences in the liquid limit and plasticity index between the natural and compacted loess (Table 5). For the samples with a dry density greater than 1.7 g/cm³, there are significant differences in the liquid limit, plasticity index, clay fraction and compression modulus between the natural and compacted loess, and there are highly significant differences in the natural water content, silt fraction and sand fraction between the natural and compacted loess (Table 6).

The results of the mean values and standard deviations of different data groups can be compared in Fig. 10. When the dry density is similar, the compacted loess can have a larger ρ_d-D , larger sand fraction and higher permeability than the natural loess, while the sampling depth, liquid limit, plastic limit, plasticity index, clay fraction, silt fraction and compression modulus of the compacted loess are significantly smaller than that of the natural loess. Besides, the specific gravities of the compacted loess and natural loess are almost the same, especially when the dry density is less than 1.7 g/cm³. In addition, the compacted loess can have higher natural water content when the dry density is less than 1.6 g/cm³, while the natural loess has higher natural water content when the dry density is greater than 1.7 g/cm³.

Results from the correlation coefficient checks

The results obtained from the correlational analysis of the compacted loess are presented in Table 7. The natural water content has a highly significant positive correlation with the clay fraction and silt fraction, while it has a highly significant negative correlation with the sand fraction. And there is a significant positive correlation between natural water content and well depth, but the correlation between permeability coefficient and well depth is significantly negative. The permeability coefficient is also negatively correlated with the dry density (significant)

and liquid limit (highly significant). The liquid limit is positively correlated with the plastic limit (significant) and plasticity index (highly significant), while the correlation between the plastic limit and plasticity index is significantly negative. And the liquid limit has a significant positive correlation with the clay fraction and silt fraction, and a significant negative correlation with the sand fraction. Similarly, the plastic limit has a highly significant positive correlation with the silt fraction, and a significant negative correlation with the sand fraction. Moreover, the clay fraction, silt fraction and sand content are highly correlated, and the correlation between the clay fraction and silt fraction is positive.

Table 7 The correlation coefficients between every two indices of the compacted loess.

	Well depth	w	ρ_d	G_s	LL	PL	Ip	N_{cl}	N_{si}	N_{sa}	E_s	k
Well depth	1.000											
w	0.012	1.000										
ρ_d	0.423*	0.246	1.000									
G_s	0.142	-0.128	-0.165	1.000								
LL	0.200	0.348	0.283	0.062	1.000							
PL	-0.009	0.002	0.197	0.118	0.447*	1.000						
Ip	0.157	0.356	0.117	0.003	0.559**	-0.406*	1.000					
N_{cl}	0.109	0.785**	0.314	-0.197	0.474*	0.214	0.290	1.000				
N_{si}	-0.034	0.516**	0.116	-0.198	0.458*	0.507**	0.036	0.773**	1.000			
N_{sa}	0.005	-0.569**	-0.138	0.237	-0.482*	-0.463*	-0.083	-0.825**	-0.991**	1.000		
E_s	0.018	0.060	0.195	0.058	-0.020	0.276	-0.285	0.082	0.118	-0.063	1.000	
k	-0.426*	-0.244	-0.408*	-0.127	-0.538**	-0.287	-0.311	-0.205	-0.089	0.097	-0.176	1.000
* means p-value < 0.05, indicating statistical significance;												
** means p-value < 0.01, indicating highly statistical significance.												

Table 8 The correlation coefficients between every two indices of the natural loess.

	Well depth	w	ρ_d	G_s	LL	PL	Ip	N_{cl}	N_{si}	N_{sa}	E_s	k
Well depth	1.000											
w	0.641**	1.000										
ρ_d	0.774**	0.674**	1.000									
G_s	0.355	0.285	0.359	1.000								
LL	0.400*	0.690**	0.591**	0.101	1.000							
PL	0.272	0.258	-0.127	-0.024	0.225	1.000						
Ip	0.375	0.534**	0.739**	0.229	0.758**	-0.323	1.000					
N_{cl}	0.413*	0.862**	0.643**	0.462*	0.758**	0.155	0.672**	1.000				
N_{si}	0.425*	0.808**	0.558**	0.362	0.815**	0.197	0.658**	0.855**	1.000			
N_{sa}	-0.470*	-0.855**	-0.602**	-0.413*	-0.828**	-0.248	-0.672**	-0.932**	-0.976**	1.000		
E_s	0.066	0.387	0.172	0.261	0.192	0.039	0.142	0.429	0.323	-0.326	1.000	
k	-0.668**	-0.863**	-0.752**	-0.517**	-0.637**	-0.096	-0.635**	-0.875**	-0.736**	0.808**	-0.215	1.000
* means p-value < 0.05, indicating statistical significance;												
** means p-value < 0.01, indicating highly statistical significance.												

The results obtained from the correlational analysis of the natural loess are presented in Table 8. On the whole, the clay fraction, silt fraction and sand content are significantly or highly significantly correlated with the other indices except for the plastic limit. And there is a highly significant positive correlation between the clay fraction and silt fraction, while the correlation between clay fraction and sand fraction, and the correlation between silt fraction and sand fraction, are highly significant negative, as same as the compacted loess. Just like the significant correlations between the soil fractions and the well depth, the natural water content, dry density, liquid limit and plasticity index all have a highly significant positive correlation with the clay fraction and the silt fraction, and a highly significant negative correlation with the sand fraction. Besides, the specific gravity has a significant positive correlation with the clay fraction, and a significant negative correlation with the sand fraction. Here the liquid limit is also positively correlated with the plasticity index (highly significant). But unlike the compacted loess, the liquid limit and plasticity index have highly significant positive correlations with the natural water content and the dry density, rather than the plastic limit. Moreover, there are highly significant positive correlations among the well depth, natural water content and dry density. And there is a significant positive correlation between the well depth and the liquid limit. What's more, the permeability coefficient of the natural loess has more kinds of highly significant negative correlation indices than the compacted loess, such as natural water content, specific gravity, clay fraction, silt fraction, etc. And it has a highly significant positive correlation with the sand fraction.

Discussion

The above mentioned results have demonstrated that the physical and mechanic properties of the manual filling compacted loess are quite different from those of the natural sedimentary loess.

By analyzing the dry density and ρ_d - D values of the natural and compacted loess (Fig. 4b, Fig. 9, Table 3), one can find that the heterogeneous level of the compacted loess in the same burial depths is greater than that of the natural loess. However, the standard deviations in Table 3 indicate that considering different burial depths, the properties of the compacted loess are more homogeneous. A possible explanation for this might be that natural loess blocks from different locations and layers were mixed together then compacted directly into new layers during the construction process. It should be noticed that loess is a kind of Quaternary aeolian deposit and the loesses from different layers have different properties, as does its dry density. The natural loess in the same buried depth was formed at the same time and has undergone geological evolution for millions of years which made its physical properties basically consistent, and the natural loesses of different layers differ greatly in physical properties due to different formation ages and paleoclimatology (Liu, 1985). And the new compacted loess stratum did not undergo such long-term geological evolution. These factors provide further support to explain why the compacted loesses from the same region have different dry density in the same depth, and why the natural loesses from different regions have similar dry density distribution (Fig. 9). These factors can also explain the correlation coefficient difference between Table 7 and Table 8, that the natural loess has more pairwise correlated indicators and higher correlation coefficients compared with the compacted loess. It needs to be stressed that

the dry density of compacted loess is significantly correlated to the well depth, which is mainly due to the compaction of underlying soil mass under the gravity of continuously thickened overlying soil mass during the construction process.

Previous studies evaluating Quaternary loess have shown that the soil fractions of the loess formed in different periods are different due to the difference in paleoclimate (Liu, 1985; Lu et al., 1997; Muhs et al., 2014). The loess formed in the dry and cold environment has more sand or silt particles, while the loess formed in the hot and humid environment has more silt or clay particles (Lu et al., 1997). And the old loess generally contains more fine particles than the new loess (Liu, 1985). The loess to infill the valleys was taken from the tops of hills, which is generally new loess. That might be the reason why the clay fraction and silt fraction of the compacted loess are significantly fewer than the natural loess (Table 3, Fig. 10h, Fig. 10i). Paleoclimate and paleoenvironment can explain the obvious soil fraction changes of the natural loess in Fig. 6. As the changes of the compacted loess have no such rule, the difference of the soil fractions between the two kinds of loess in the same depth can fall into three situations: 0 ~ 5m, 5 ~ 15m, > 15m. This difference, in turn, leads to differences in the natural water content and permeability coefficient (Fig. 4a, Fig. 7b). The results in Table 7 and Table 8 can also indicate that. Moreover, considering the paleoclimate, paleoenvironment, tectonic movement and hydrogeology conditions, natural sedimentary loess of the same depth in different regions can have different natural water content (Fig. 8b). In particular, as the loess specimens above 5m are close to the surface and their natural water content is greatly affected by rainfall, the difference among all the data is not obvious (Fig. 8).

Another significant conclusion can be drawn from the data in Table 7 and Table 8, that the liquid limit increases as the clay fraction and silt fraction increase. This relationship may partly be explained by the increased ability to absorb water in the presence of more fine particles (Atterberg, 1911; Haigh et al., 2013; Shimobe and Spagnoli, 2019). The positive correlation between the plasticity index and the clay or silt fractions of the natural loess can also indicate that. Surprisingly, the results of the plastic limit and plasticity index in Table 7 is quite different from Table 8. It is difficult to explain that, but it might be related to the heterogeneous of compacted loess in the same layer. And the heterogeneous might be an important reason for the large variation in monitoring data (Fig. 8a), as the monitoring equipment can only contact with a certain point of soil even cracks and leakage are commonly found in the filled body (Zhang et al., 2019).

Furthermore, Table 3 and Fig. 10 have shown that the liquid limit, plastic limit, plasticity index and compression modulus of the compacted loess are significantly smaller than that of the natural loess, suggesting that the compacted loess is more easily to deform. In other words, natural loess is more stable. What needs to be emphasized is that the natural sedimentary loess samples in this study are Lishi loess (Q2) and Wucheng loess (Q1). Several reports have shown that the Lishi loess and Wucheng loess are stable in structure and will not collapse under normal circumstances (Li and Miao, 2006; Li et al., 2015; Li et al., 2013). The Lishi loess with relatively high dry density and the Wucheng loess can be used as a good foundation for the building. Thus, it is of great significance to compare the property differences between the manual filling compacted loess and the natural sedimentary loess with similar densities for understanding the site stability.

Here the compression modulus is an important parameter to qualitatively analyze the stability and future settlement deformation of the site. By analyzing the independent-samples t-tests results of different data groups (Table 4, Table 5, Table 6), one can find that there is no significant difference in the compression modulus between the natural (Q2) and compacted loess only when the samples' dry density is greater than 1.6 g/cm³ and less than 1.7 g/cm³. When the dry density is less than 1.6 g/cm³, the natural (Q2) and compacted loess have significantly different compression modulus and dry density. However, when the dry density is greater than 1.7 g/cm³, the natural (Q1) and compacted loess have significantly different compression modulus, clay fraction, silt fraction and sand fraction. The results indicate that the difference of compression modulus between the compacted loess and natural loess is mainly controlled by the dry density and the particle composition.

The previous statistics of dry density of loess in different sedimentary ages show that the dry density of Lishi loess is about 1.4 ~ 1.7 g/cm³, and the dry density of Wucheng loess is generally greater than 1.7 g/cm³ (Li and Miao, 2006). It can therefore be assumed that, if both the compacted loess and natural loess are Lishi loess (Q2), dry density is the most important factor affecting the stability of compacted loess (Table 4, Table 5). When the dry density is greater than 1.7 g/cm³, here the natural loess is Wucheng loess while the compacted loess is still Lishi loess (Q2). The stability difference between the natural and compacted loess is no longer controlled by dry density, but by particle composition (Table 6). And the decreasing compression modulus is closely related to the water content (Fig. 10b, Fig. 10i).

Moreover, Fig. 10c and Fig. 10l have shown that the compacted loess cannot have the same compression modulus as the natural loess even though the dry density appears to be similar. As mentioned above, finer particles are one of the reasons. The natural loess has larger clay and silt fractions than the compacted loess (Fig. 10h, Fig. 10i). The small-size particles (< 50µm) are able to enlarge the area of inter-aggregate contacts and hence stabilize the soil skeleton (MuñOz-Castelblanco et al., 2012; Ng et al., 2019). Another possible explanation is that the soil strength is governed by the behavior of the coating and bonding at the particle contacts (Tan, 1988). Due to the long period of structural evolution, the clay particles and calcite cementation reinforced existing grain contacts in the natural loess (Li et al., 2018; Zuo et al., 2020). However, in the compacted loess, the clay particles seemed to mainly form silt-size aggregates or adhere to the surface of the silt grains instead of the clay connections between the particles, and the calcite cementations were absent in the compacted loess (Mu et al., 2020).

Hence, it could conceivably be concluded that the soil skeleton of the compacted loess was expected to be weaker than that of natural loess. In addition, what is also possible is that the compacted loess cannot mirror the natural loess in microstructure even though the dry density appears to be modeled well. Zhang et al. (2020) showed that the compacted loess would have more macropores ($d > 13 \mu\text{m}$) than natural loess under the same condition. Therefore, the compacted loess may have more compressible space.

Laboratory tests have shown that loess samples undergone one-time pressing have more uniform pore size distributions than the bumped loess (Meng et al., 2019). Similarly, the weight of the overlying soil appears to be a large-scale one-time pressing on the underlying compacted loess. Under the dead load, the macro-pores and part of the macro-cracks can be compressed. The large pores can be broken into medium pores and some small pores. When the overburden reaches a certain thickness, the dead load can be large enough that the medium pores will be broken into small pores. Only in this case, the compacted loess can be as stable as the natural loess (Zhang et al., 2020). The tendency that the dry density and compression modulus increased with depth (Fig. 4a, Fig. 7a and Fig. 9a) means that the underlying compacted loess is becoming more stable. And for the Lishi loess, the dry density of this kind of stable compacted loess should not be less than 1.64 g/cm^3 (Table 5). Besides, the hydrological conditions can also affect the evolution of compacted loess. The infiltrating water can dissolve soluble salts, causing transportation and reprecipitation of calcium carbonates and reinforcement of existing pores by cements (Cilek, 2001; Li et al., 2018; Smalley et al., 2006). And this long period of structural evolution can also reinforce the contacts of the clay particles (Zuo et al., 2020). For the compacted loess above the water table, this hydrological action is more prevalent within 5 m below the surface (Fig. 4a, Fig. 8). Hence, it could conceivably be hypothesized that under a combination of external hydrologic conditions and dead weight, the compacted loess will become more stable.

Conclusion

Based on two exploration wells in an MBCC site, the natural water content, dry density, specific gravity, liquid limit, plastic limit, plasticity index, clay fraction, silt fraction, sand fraction, compression modulus, and permeability coefficient of the natural sedimentary loess (Lishi and Wucheng loess) and manual filling compacted loess were obtained from several soil tests. The statistical theories such as t-test and correlation coefficient checks were carried out by SPSS to analyze the difference between the two kinds of loess, and the degree of correlation among various indicators. Besides, 14 groups of exploration well data about natural water content and dry density in 8 studies were collected and analyzed to supplement the existing data.

From this research, several important conclusions can be reached:

- 1) There are significant differences in physical properties between the natural sedimentary loess and manual filling compacted loess.
- 2) The heterogeneous level of the manual filling compacted loess is greater than that of the natural sedimentary loess in the horizontal direction, and smaller than that of the natural sedimentary loess in the vertical direction.
- 3) The loess which has more small-size particles ($< 50\mu\text{m}$) would have greater liquid limit.
- 4) Compared with the natural sedimentary loess (Lishi and Wucheng loess), the liquid limit, plastic limit, plasticity index and compression modulus of the manual filling compacted loess are smaller. This highlights that the manual filling compacted loess is more easily deformed.
- 5) The difference of compression modulus between the compacted loess and natural loess is mainly controlled by dry density when the sample's dry density is less than 1.7g/cm^3 . And it will be mainly controlled by particle composition when the dry density is greater than 1.7g/cm^3 .
- 6) Under a combination of external hydrologic conditions and dead weight, the compacted loess will become more stable.

Declarations

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Contributions

Shengwen Qi, Songfeng Guo, Yaguo Zhang conceived and designed the test. Linxin Zhang, Shengwen Qi, Yaguo Zhang, Zhiqing Li and Yongtang Yu participated in the sampling process. Linxin Zhang, Lina Ma and Xiaokun Hou contributed laboratory experimental steps. Linxin Zhang, Shengwen Qi, Lina Ma, Xiaokun Hou and Yu Zou contributed analytical steps. Shengwen Qi and Jianbing Peng obtained financial support for the project. Linxin Zhang drafted the manuscript, and Shengwen Qi revised the manuscript. All authors discussed the article and gave their comments.

Ethics declarations

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figures

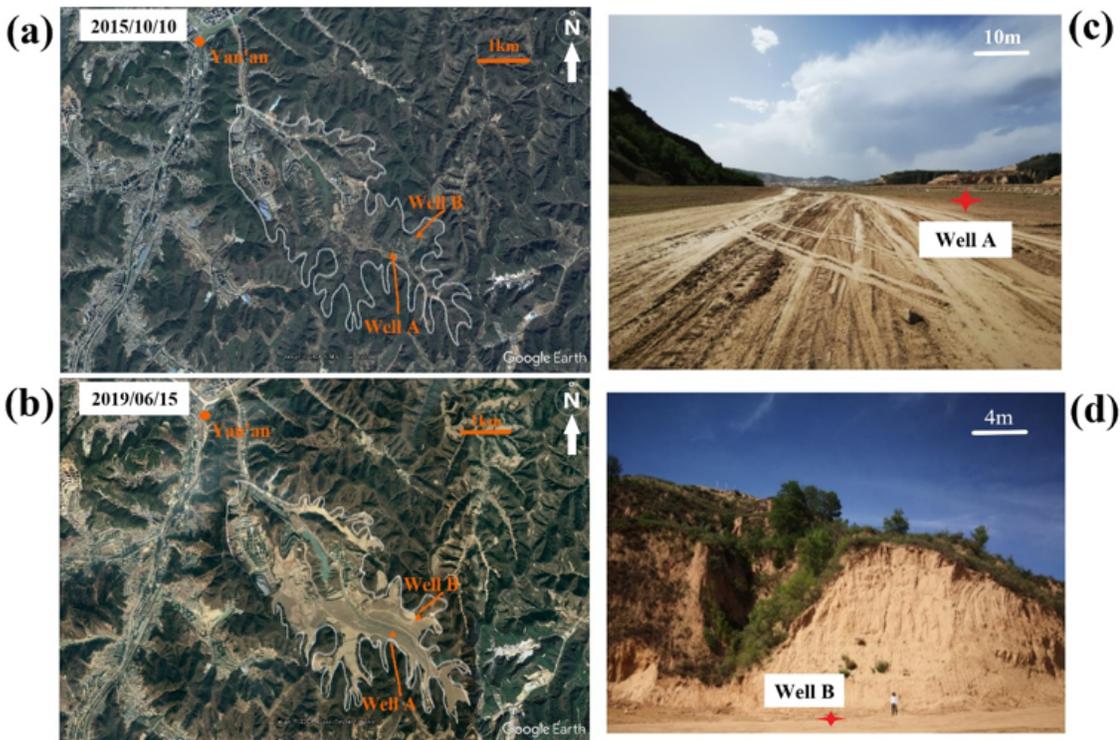


Figure 1

Location of the sampling site: (a) satellite image from google earth of the study area before construction; (b) satellite image from google earth of the study area after construction; (c) the location of exploration well for compacted loess; (d) the location of exploration well for natural loess.

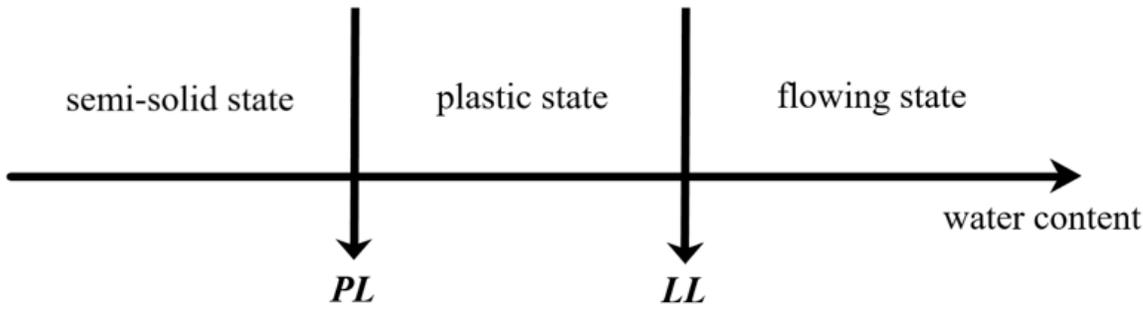


Figure 2

Soil consistency and plasticity behavior according to water content, which increases from left to right on the diagram.

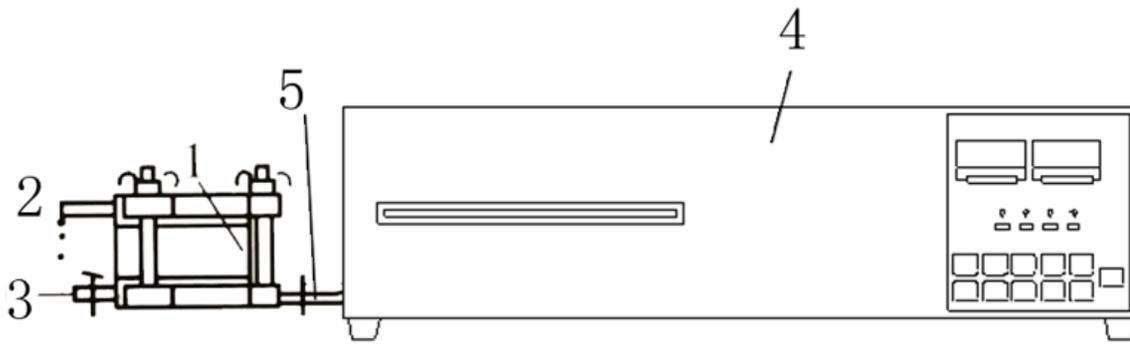


Figure 3

Schematic of the equipment for determining permeability: 1- permeable container; 2- outlet pipe; 3- exhaust pipe; 4- water pressure controller; 5- water inlet pipe.

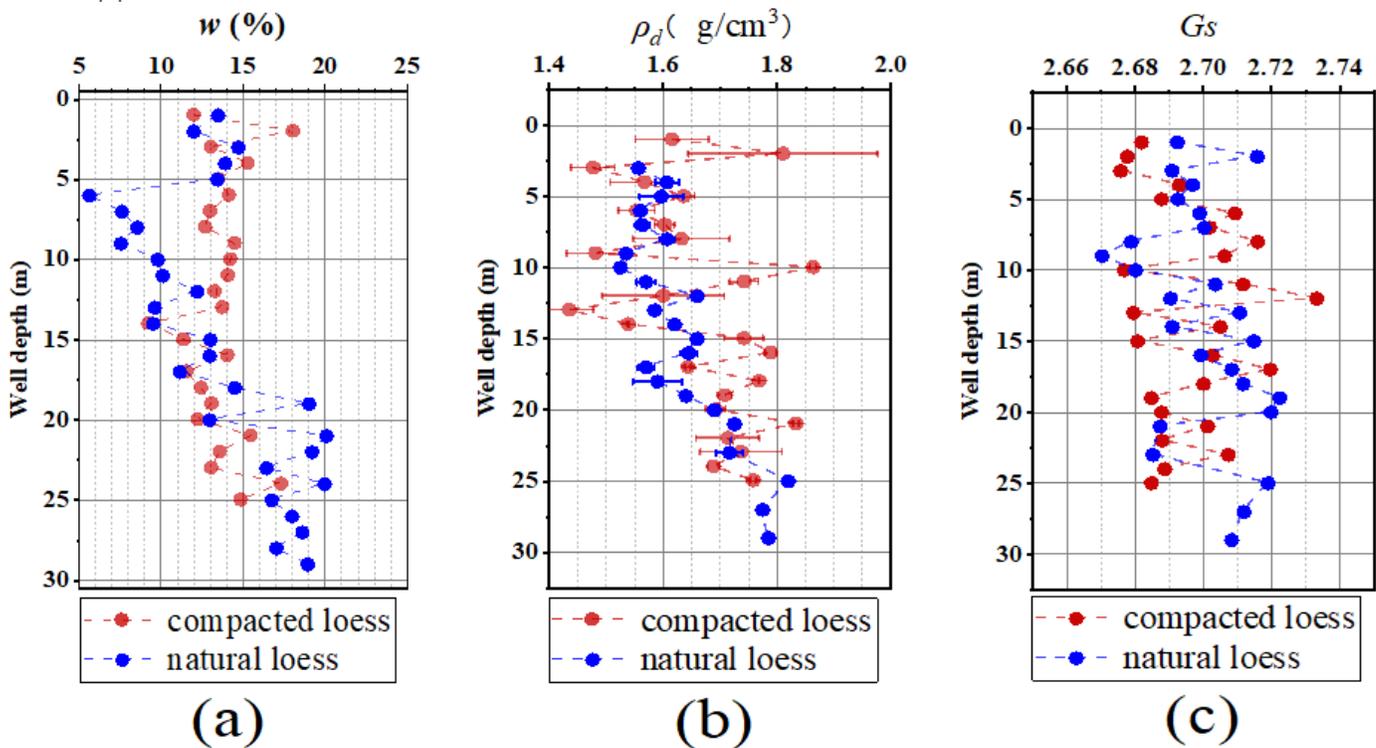


Figure 4

The variation of basic index properties with well depth: (a) natural water content vs. well depth; (b) dry density vs. well depth; (c) specific gravity vs. well depth.

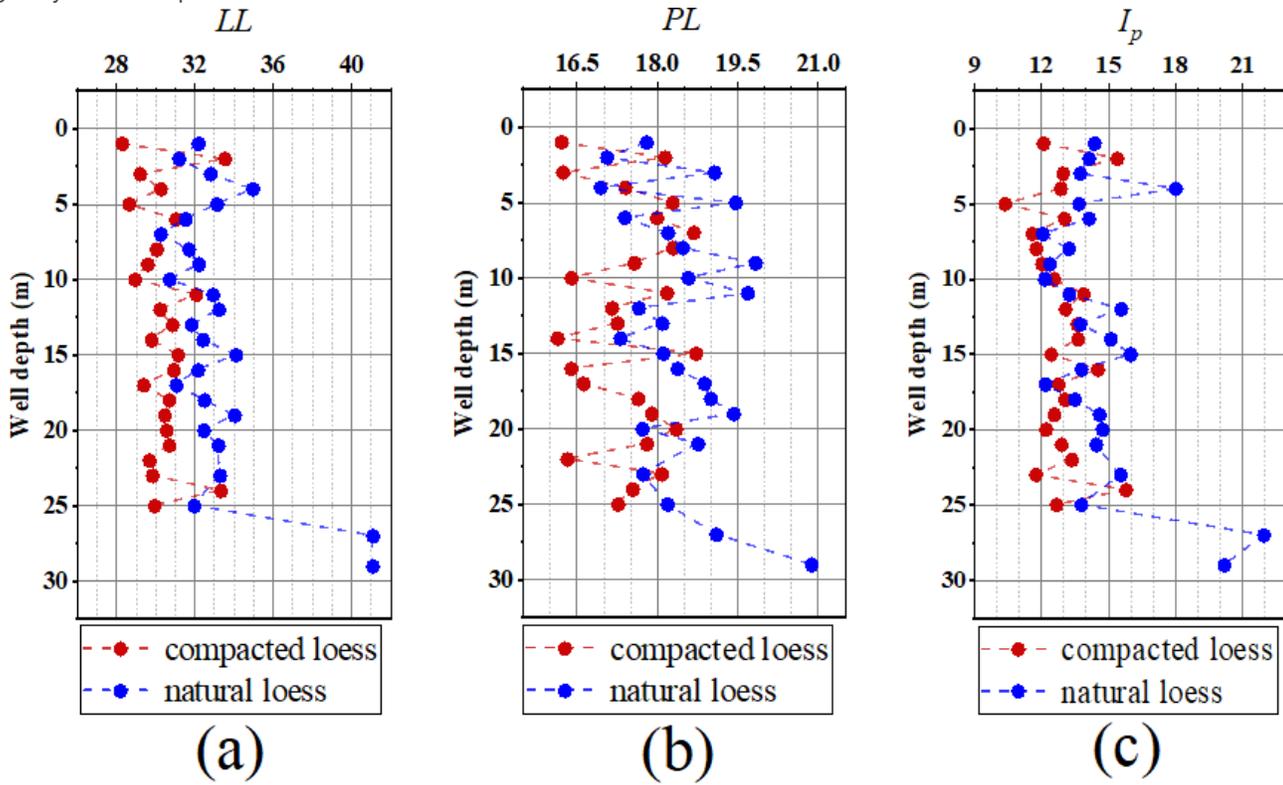


Figure 5

The variation of consistency and plasticity properties with well depth: (a) liquid limit vs. well depth; (b) plastic limit vs. well depth; (c) plasticity index vs. well depth.

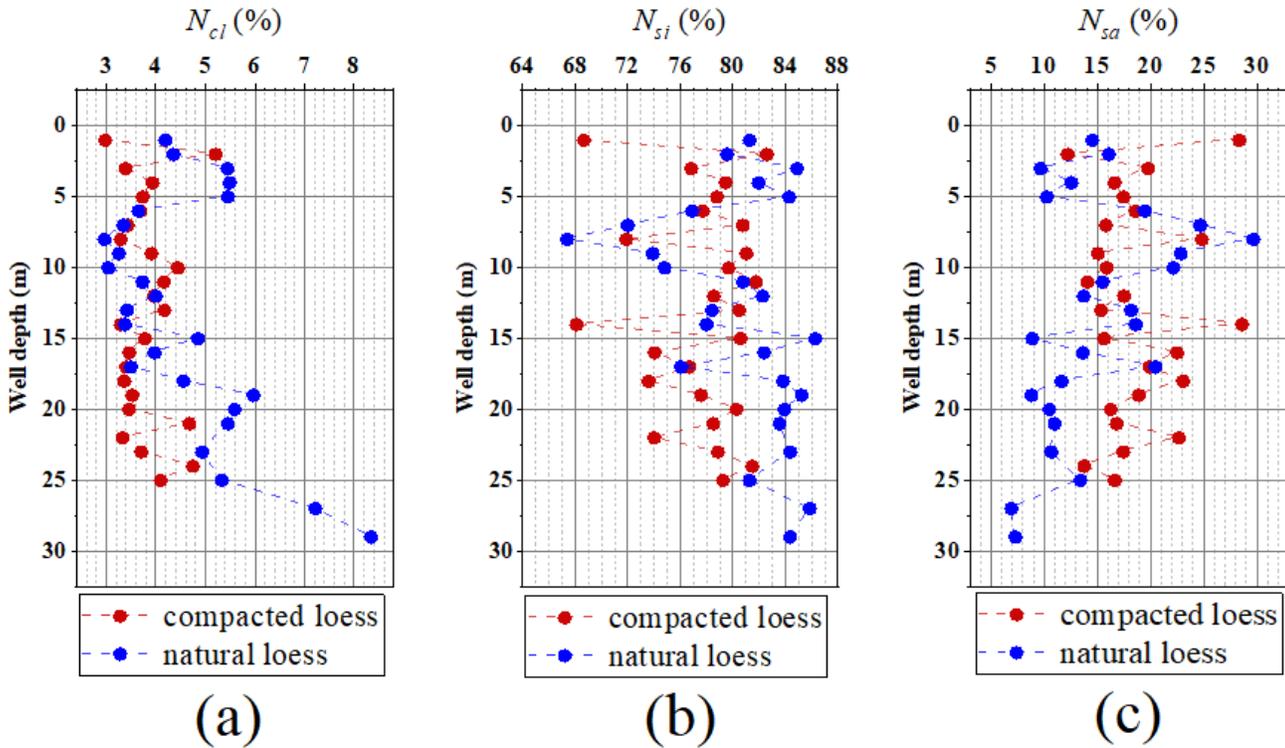


Figure 6

The variation of percentage of soil fractions with well depth: (a) clay fraction vs. well depth; (b) silt fraction vs. well depth; (c) sand fraction vs. well depth.

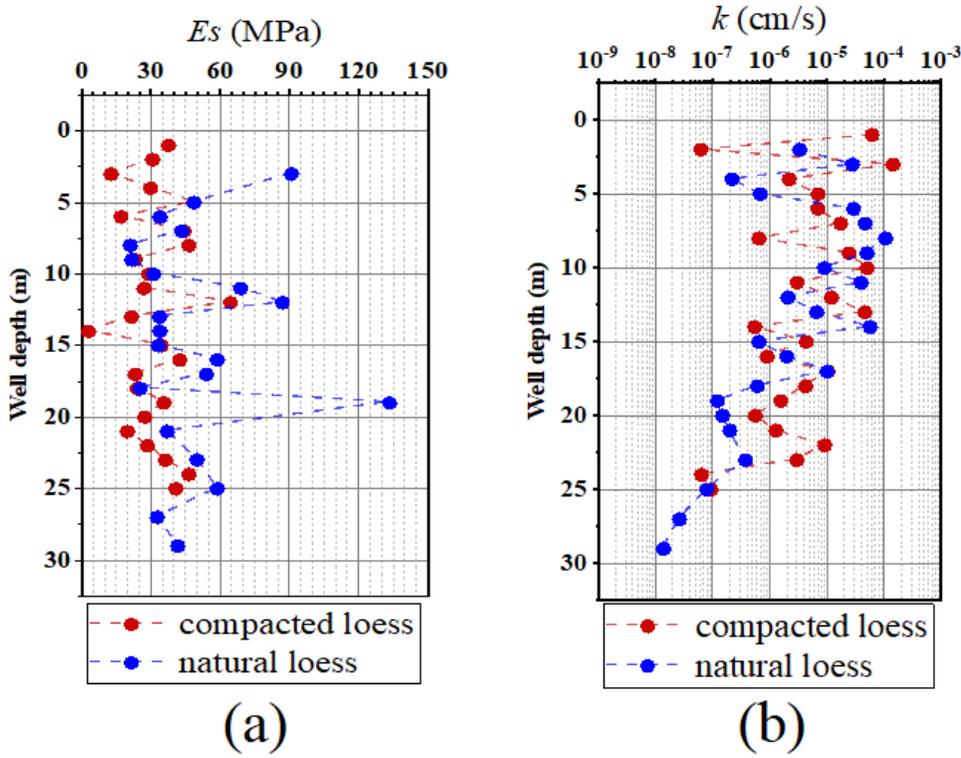


Figure 7

The variation of compressibility and permeability with well depth: (a) compression modulus vs. well depth; (b) permeability coefficient vs. well depth.

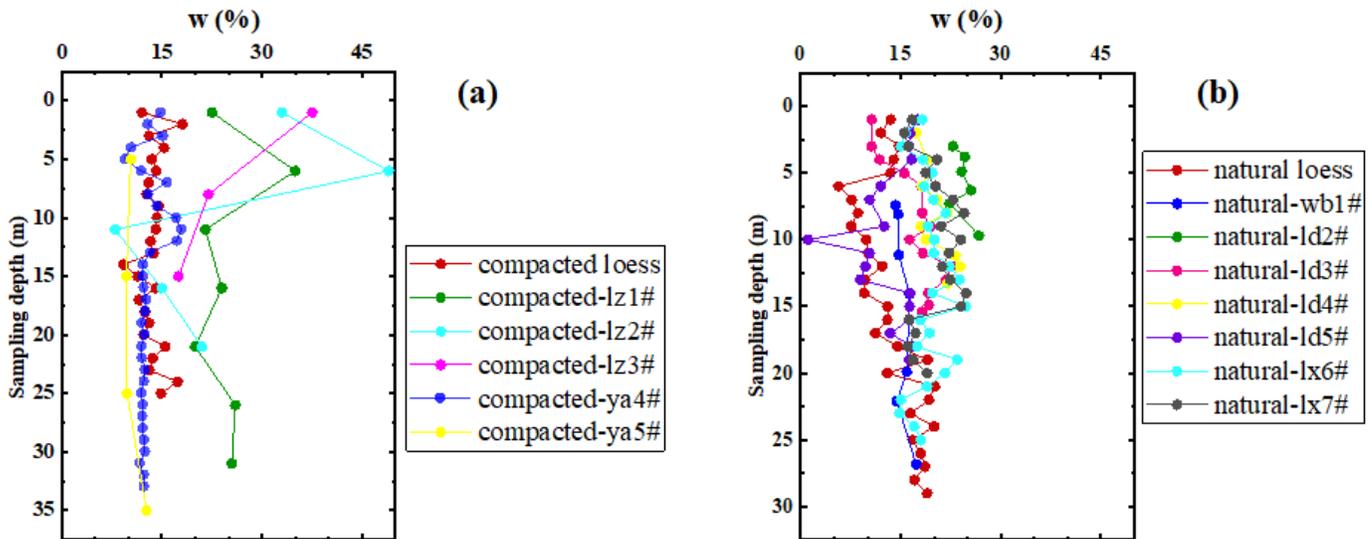


Figure 8

The variation of natural water content with sampling depth: (a) change curves of the compacted loess; (b) change curves of the natural loess.

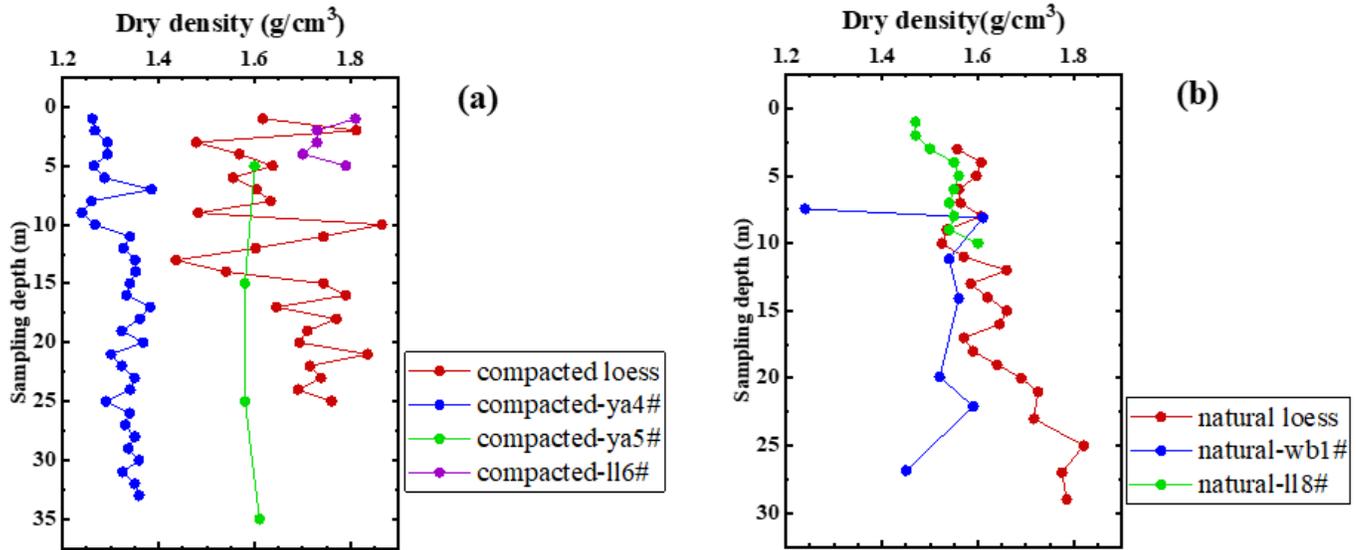


Figure 9

The variation of dry density with sampling depth: (a) change curves of the compacted loess; (b) change curves of the natural loess.

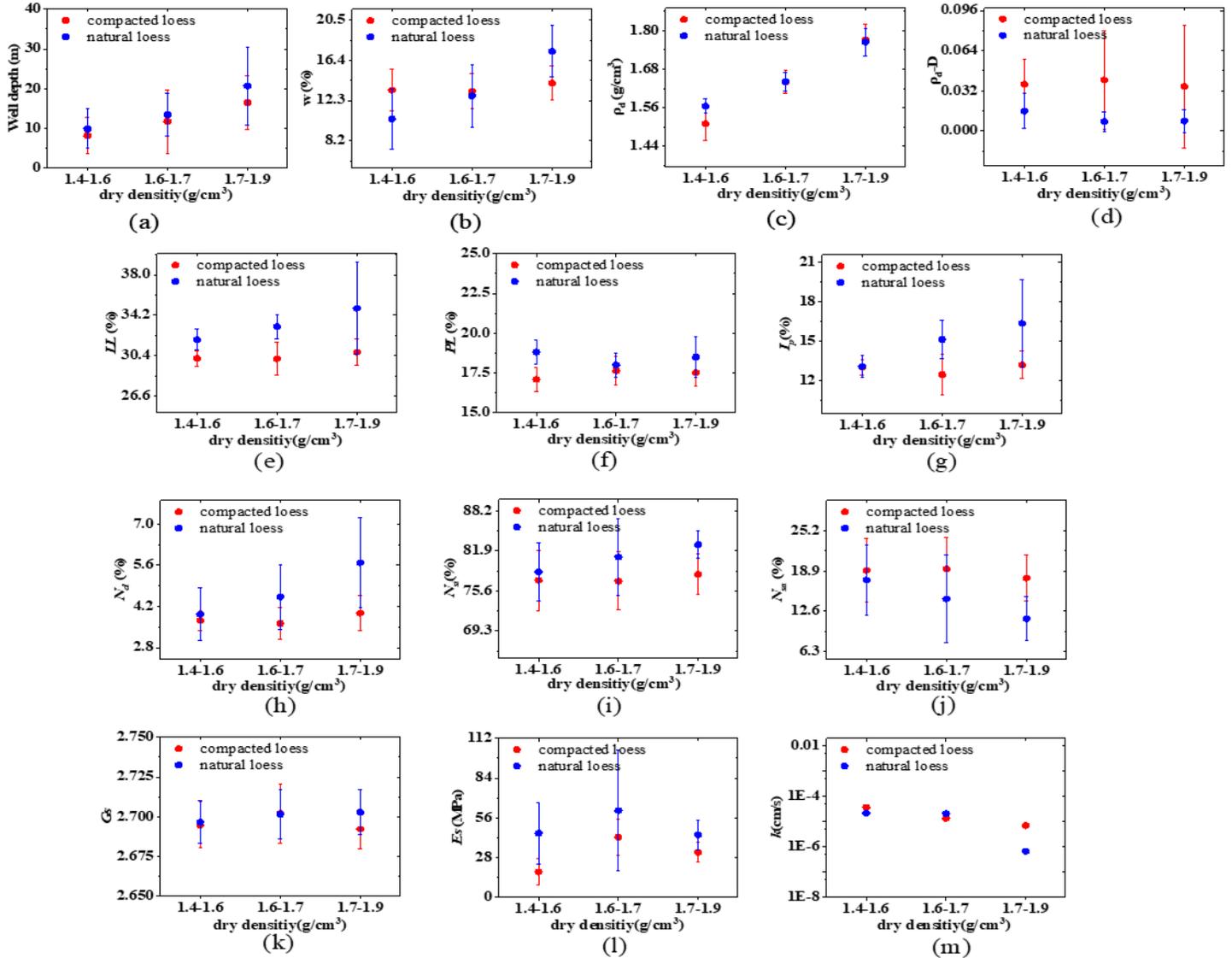


Figure 10

The mean values and standard deviations of different data groups ($\rho_d < 1.6 \text{ g/cm}^3$, $1.6 \text{ g/cm}^3 < \rho_d < 1.7 \text{ g/cm}^3$, $\rho_d > 1.7 \text{ g/cm}^3$)