Full length article

Geometrical appearance and spatial arrangement of structural blocks of the Malan loess in NW China: implications for the formation of loess columns

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\textbf{ARTICLE INFO}

\textbf{ABSTRACT}

Loess, as one of the main Quaternary deposits, covers approximately 6% of the land surface of the Earth. Although loess is loose and fragile, loess columns are popular and they can stand stably for hundreds of years, thereby forming a spectacular landform. The formation of such special column-shaped soil structures is puzzling, and the underlying fundamentals remain unclear. The present study focuses on quantifying and examining the geometrical shape and spatial alignment of structural blocks of the Malan loess at different locations in the Loess Plateau of China. The structural blocks under investigation include clay- and silt-sized particles, aggregates, fragments, lumps, and columns, which vary in size from microns to tens of meters. Regardless of their size, the structural blocks of the Malan loess are found to be similar in shape, i.e., elongated with a length-to-width ratio of approximately 2.6. The aggregates, fragments, lumps, columns, and macropores between aggregates exhibit strong concentration in the vertical or subvertical alignment. These phenomena imply that the Malan loess is anisotropic and it is composed of a combination of vertically aligned strong units and vertically aligned weak segments. Based on this, "vertiloess" structure is proposed to denote this combination. The vertiloess structure prevents horizontal erosion, but favors spalling, peeling, toppling, falling and cracking-sliding of vertical loess pieces, thereby forming loess columns.

1. Introduction

Loess is a clastic, predominantly silt-sized windblown nonstratiﬁcation of typical loess landforms. Loess platforms (yuan, in Chinese), ridges (liang), and hillocks (mao) are typically classiﬁed into secondary loess landforms (; Fuller, 1922; Zhang, 1983a, 1983b; Sun, 2005). The loess–paleosol sequence in the Loess Plateau of China (LPC) is typically characterized, in terms of stratigraphy, by the continuous deposition of the Wucheng (Q1), Lishi (Q2), and Malan (Q3) layers from bottom to top (Li et al., 2018a).

Loess originates from aeolian dust accumulation, which originally prevents horizontal erosion, but favors spalling, peeling, toppling, falling and cracking-sliding of vertical loess pieces, thereby forming loess columns. The structure of present-day loess results from long-term deposition and loessification processes (Liu, 1985; Zhang, 1989; Smalley, 1995; Pécsi, 1990, 1995; Smalley et al., 2011; Smalley and Marković, 2014). Loessification broadly includes functions of biotic and abiotic processes (Lozek, 1965; Pécsi, 1990; Cilek, 2001), overburden layer compression (Sprafke and Obreht, 2016), rainfall leaching (Zhao, 2002), capillary action (Ambroz, 1947; Zhang, 1989), and surficial erosion (Gao, 1990). These processes are also the main driving forces leading to the formation of typical loess landforms. Loess platforms (yuan, in Chinese), ridges (liang), and hillocks (mao) are typically classiﬁed into ﬁrst-order landforms in loess areas (Zhang, 2000; Zhu, 2009), while loess columns (zhu), bridges (qiao), and walls (qiang), developing within ﬁrst-order landforms, are generally classiﬁed into secondary loess landforms (; Fuller, 1922; Zhang, 1983a, 1983b; Sun, 2005).

A loess column (Fig. 1) is an isolated, vertical loess block with either a cylindrical, conical, or tower shape; it is typically several meters to over ten meters high (Liu, 2016). Loess columns develop densely in typical loess zones (e.g., the Linfen and Changzhi areas in China) and clayey loess zones (e.g., Xi’an and Jingning areas) in China, while they are rarely found in sandy loess areas (e.g., Lanzhou area) (Zhu, 2009).
Loess columns can stand stably for hundreds of years under natural conditions. As loess is regarded worldwide as a fragile geological material with loose compaction, the formation of such special column-shaped structures is puzzling, and the underlying fundamentals remain unclear.

In geology, it is found that the fractal characteristics of size distribution, porosity, and pore connectivity of soils with the same origin are normally similar (Hadas, 1987; Dexter, 1988; Bartoli et al., 1991; Crawford et al., 1993; Li, 1994; Posadas et al., 2003; Guo, 2015). The geometrical shape and spatial alignment of fractures of different sizes within a rock mass unit also exhibit similarities (Okubo and Keitti, 1987; Zhang, 1984; Hirata et al., 2010; Rao et al., 2009). As small-sized loess particles and aggregates (i.e., cemented clusters of loess particles) comprise loess blocks, which in turn compose loess column, we focus, in the present study, on quantifying and examining the shape and alignment of loess structural blocks. The blocks under examination vary in size from clay-sized particles (< 5 μm) to loess columns reaching up to 30 m high. The aim is to identify the similarity or variation in loess structural blocks of different sizes in terms of shape and alignment, and to find clues to the formation of loess columns.

2. Literature review

The shape of soil particles is closely related to transport, deposition, and subsequent weathering conditions (Hu et al., 2015). Loess particles are transported through saltation and suspension under the action of wind (Zhang, 1983a, 1983b; Assallay et al., 1997; Wang et al., 1999). Particles become finer and rounder as transport distance increases due to the collision and friction among them (Hu et al., 2015). After deposition, the dissolution of soluble substances by water can further modify the shape of the particles (Yang and Li, 2012; Li, 2016).

Two main methods are available for quantifying particle shape: statistical parameters and fractal dimensions (Liu et al., 2011). Table 1 summarizes the parameters commonly used in the literature to describe particle shape and surface roughness. Our review indicates that (1) some parameters, which have the same meaning and calculation, are named differently and assigned different symbols in various references; and (2) the same term is given to different parameters/calculations. Thus, for clarity, we unified terms and symbols according to the definition/calculation of each parameter.

In general, aspect ratio, circularity, and convexity can work together efficiently to fully define the shape and surface roughness of an object. As indicated in Table 1, aspect ratio (width-to-length ratio, \( \alpha \)) and circularity (\( C_c \)) describe the overall shape of particles. The \( \alpha \) value ranges from 0 to 1. A block that is symmetrical in all axes, such as a square and a circle, has an \( \alpha \) value of 1. By contrast, strongly elongated blocks have an \( \alpha \) value that is closer to 0. \( C_c \) emphasizes overall angularity. A rounded particle (without sharp corners) has a \( C_c \) of 1, whereas an extremely angular particle has a \( C_c \) close to 0. Convexity (\( C_v \)), solidity (\( S \)), and roughness (\( \gamma \)) reflect the local smoothness or roughness of particle surface. \( C_c \) and \( S \) have values close to 0 for rough particles and values close to 1 for smooth particles, while \( \gamma \) does the opposite.

Particle arrangement in soil sedimentation is affected by deposition mode, stress condition, water condition, and the geomagnetic field (Rees, 1968; Hrouda, 1981; Oda, 1972; Johansson, 1965; Stewart et al., 2006). Wu and Yue (1997) found that the short axis of the anisotropy of the magnetic susceptibility ellipsoid of aeolian loess particles is vertically aligned. Yang et al. (2009) found that the long axis of sand that piled up by free-falling is parallel to the horizontal plane. The long axis of soil particles is generally perpendicular to the direction of the maximum principal stress (Shi and Li, 1988; Chen, 2006; Duan et al., 2017).

Table 2 lists the definitions and calculations of parameters for characterizing particle arrangement in the literature. All these parameters are derived from the particle orientation angle (\( \varepsilon \)), which is the acute angle between the major axis (\( M_\alpha \)) of a particle and the horizontal axis, and is located within the range of 0°–90° (Fig. 2). The major axis (\( M_\alpha \)) passes through the centroid of a particle, and the rotational kinetic energy of the particle that lies on this axis is the least, whereas the minor axis (\( M_\varepsilon \)) passes through the centroid and is perpendicular to the major one.

3. Methodology

In this study, loess structural blocks with different sizes were analyzed in terms of geometrical shape and spatial arrangement. The structural blocks being investigated varied from clay-sized particles to loess columns, covering a wide range of sizes. They were classified into six categories and form a continuous sequence in size as listed in Table 3: clay particle (Group I), silt particle (Group II), aggregate (Group III), fragment (Group IV), lump (Group V), and column (Group VI). This classification was done according to BS 1377-2 (British Standard Institution, 1990).

3.1. Preparation of images for structural blocks

The images used to derive the shape and arrangement parameters of the structural blocks were obtained via scanning electron microscopy (SEM) for Groups I through III, whereas photographs were taken from the field for Groups IV through VI. Locations for collecting samples and taking photographs are shown in Fig. 3. For Groups I–III, the original in-situ orientations of blocky samples were marked clearly during sampling. The blocky samples were cut into cubic specimens measuring 40 mm × 40 mm × 40 mm without changing the orientation in laboratory. The cubic specimens were stored in a cool and ventilating chamber to allow them to dewater and dry before they were soaked in a solution of epoxy resin, acetone, ethylene diamine, and dibutylphthalate in a vacuum environment. Once a specimen is hardened with the penetration of epoxy solution, it was sliced vertically, polished, and coated to prepare thin sections for SEM examination (Wang, 2010). In this study, the electron microscope used for taking photos of thin sections was HITACHI TM-2000, with a maximum magnification of 10,000 ×.

The photographs for structural blocks in Groups IV through VI were directly taken from the fields in Xiangning, Daning, Xi, and Ji Counties in Southern and Central Shanxi Province, Luochuan area in Shaanxi Province, and Lanzhou area in Gansu Province of China (Fig. 3). When the pictures were taken, the camera was oriented normally to the exposure to avoid distortions. The representative images for each group are shown in Fig. 4.

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**Fig. 1.** Loess column (Photos taken by Y.R. Li in the National Geological Park, Luochuan, Shaanxi, China on 26 October 2014).
Table 1  
Common parameters used in the literature to characterize particle shape and surface roughness.

<table>
<thead>
<tr>
<th>Unified term</th>
<th>Symbol</th>
<th>Formula</th>
<th>Terms used in literature</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspect ratio</td>
<td>$\alpha$</td>
<td>$W/L$</td>
<td>Aspect ratio</td>
<td>Chen et al., 2005; Palasamudram and Bahadur, 1997</td>
</tr>
<tr>
<td>Elongation</td>
<td>$E$</td>
<td>$1 - L_a/W_a$</td>
<td>Elongation</td>
<td>Malvern, 2013</td>
</tr>
<tr>
<td>Flatness</td>
<td>$e$</td>
<td>$L_e/W_e$</td>
<td>Flatness</td>
<td>Liu et al., 2011</td>
</tr>
<tr>
<td>Overall contour coefficient</td>
<td>$\beta$</td>
<td>$\pi D/P$</td>
<td>Overall contour coefficient</td>
<td>Liu et al., 2011</td>
</tr>
<tr>
<td>Circularity</td>
<td>$C_i$</td>
<td>$\frac{2 \sqrt{\pi}}{\pi}$</td>
<td>Circularity</td>
<td>Malvern, 2013</td>
</tr>
<tr>
<td>HC</td>
<td>$HC$</td>
<td>$\frac{4\pi A}{P^2}$</td>
<td>HS circularity</td>
<td>Malvern, 2013</td>
</tr>
<tr>
<td>Roundness</td>
<td>$R$</td>
<td>$4\pi A/\lambda^2$</td>
<td>Roundness</td>
<td>Wu, 2014</td>
</tr>
<tr>
<td>HS roundness</td>
<td>$HR$</td>
<td>$(P/P_c)^2$</td>
<td>Silhouette coefficient</td>
<td>Wu, 2014</td>
</tr>
<tr>
<td>Roughness</td>
<td>$\gamma$</td>
<td>$P^2 / C^2$</td>
<td>Convex-concave</td>
<td>Kong and Peng, 2011</td>
</tr>
<tr>
<td>Oriented fractal dimension</td>
<td>$\epsilon$</td>
<td>$\frac{\sum_0^\pi F_2(\theta) \log R_2(\theta)}{M}$</td>
<td>Oriented fractal distribution function</td>
<td>Wang et al., 2001</td>
</tr>
<tr>
<td>Solidity</td>
<td>$S$</td>
<td>$\frac{A}{A_e}$</td>
<td>Solidity</td>
<td>Mora and Kwan, 2000</td>
</tr>
<tr>
<td>Fullness ratio</td>
<td>$F$</td>
<td>$\frac{\sum \theta}{\pi} \times 100%$</td>
<td>Fullness ratio</td>
<td>Mora and Kwan, 2000</td>
</tr>
<tr>
<td>Convexity</td>
<td>$C_o$</td>
<td>$\frac{A_e}{P}$</td>
<td>Convexity</td>
<td>Malvern, 2013</td>
</tr>
</tbody>
</table>

Note: $L$ – maximum length of particle. $W$ – ratio of area to L of particles; $L_a$ – projection length of particle onto major axis (Fig. 2); $W_a$ – projection length of particle onto minor axis (Fig. 2); $L_e$ – maximum Feret diameter; $W_e$ – minimum Feret diameter; $D$ – actual diameter; $P$ – perimeter; $A$ – actual area; $P_c$ – convex hull perimeter; $C$ – perimeter of the circumscribed ellipse of particle; $R_e$ – radius of inscribed circle of particle; $R_c$ – radius of circumscribed circle of particle; $P_e$ – perimeter of standard ellipse with the same area and flatness of particle; $A_e$ – area of the largest inscribed ellipse with the same length $L/W$ of particle; $A_e$ – area of the convex hull; and $A_c$ – area of the circle with the same perimeter as the particle.

Table 2  
Common parameters used in the literature to characterize particle arrangement.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Formula</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Directional frequency</td>
<td>$F_i$</td>
<td>$\frac{m}{M} \times 100%$</td>
<td>Shi, 1995</td>
</tr>
<tr>
<td>Directional probability entropy</td>
<td>$H_0$</td>
<td>$-\sum_1^\infty F_i(z) \log R_i(z)$</td>
<td>Shi, 1995; Wu, 1991</td>
</tr>
<tr>
<td>Orientation distribution function</td>
<td>$D_i$</td>
<td>$\frac{\sum_0^\pi F_2(\theta) \log R_2(\theta)}{M}$</td>
<td>Wang et al., 2001</td>
</tr>
<tr>
<td>Oriented fractal dimension</td>
<td>$D_{ii}$</td>
<td>$\frac{\sum_0^\pi F_2(\theta) \log R_2(\theta)}{M}$</td>
<td>Hu et al., 2001</td>
</tr>
<tr>
<td>Anisotropy rate</td>
<td>$I_i$</td>
<td>$\frac{\theta - \beta - \epsilon}{\beta}$</td>
<td>Shi et al., 1995; Shi, 1995</td>
</tr>
</tbody>
</table>

Notes: $m_i$ – number of particles in a range of orientation angles; $M$ – total number of particles; $\epsilon$ – orientation angle; $m_i$ – number of particles in the range of $[\mu - \sigma; \mu + \sigma]$ – mean orientation angle; $j$ – standard deviation of orientation angles; $\beta$ – increment of orientation angle; $P_i$ – probability of particles whose orientation angles are within $\theta_i$; $R$ – length of major axis; and $\tau$ – length of minor axis.

Fig. 2. Definition of orientation angle ($\epsilon$), which is the acute angle between the major axis ($M_a$) of a particle and the horizontal, and is located within the range of 0–90°. $M_i$ is the minor axis, which passes through the centroid of the particle and is perpendicular to $M_a$ (Malvern, 2013).

3.2. Image processing

For extracting loess structural blocks, the SEM images (Groups I–III) and photos (Groups IV–VI) were first digitized by importing them into AutoCAD to draw the boundaries of each block and then filling them in solid black. Then, the structural blocks were manually separated without changing their arrangement. This technique is effective with the exception of aggregate (Group III) as recognizing the boundary of aggregates through visual examination is difficult. To solve this problem, we adopted the watershed algorithm and performed it in MATLAB to identify the boundaries of aggregates before the SEM images were processed in AutoCAD. The watershed transformation treats the SEM image like a topographic map, with the brightness of each point representing its height. The basic idea consists of placing a water source in each regional minimum in the relief, to flood the entire relief from sources, and build barriers when different water sources meet. The resulting set of barriers constitutes a watershed, which is taken as the boundary of aggregate.

Fig. 5 shows the structural blocks extracted from images and photos for each group. The numbers of extracted structural blocks are 298, 701, 218, 350, 219, and 232 for Groups I through VI, respectively. The Malvern Image Analysis system (Malvern, 2013) was then used to measure the shape and arrangement parameters for the extracted structural blocks. The length ($L$) of a block is determined as the projection length of the block onto its major axis, while the width ($W$) is the projection length onto its minor axis. The convex hull perimeter ($P_h$) and perimeter ($P$) of a block are determined by counting the pixels on the boundary of the convex envelope and the block itself, respectively. The area ($A$) is the area of pixels over a block. With these parameters, $A$, $C_o$, $C_p$, and $\epsilon$ for each structural block were calculated according to Tables 1 and 2.
4. Results

Fig. 6 shows the statistical distribution of the shape parameters (i.e., \(\alpha\), \(C_i\), and \(C_o\)) of structural blocks in each group. The mean values of \(\alpha\), \(C_i\), and \(C_o\) of structural blocks in Group I are 0.38, 0.82, and 0.96, respectively. These values indicate that the clay-sized particles in loess have a subelliptical-rounded-smooth shape. In this study, “elongated” describes the overall shape of a particle, “rounded” indicates overall angularity, and “smooth” denotes local surface roughness. The mean values for Group II indicate that the shape of the silt particles belonging to this group is highly similar to that of clay particles. The mean values of \(\alpha\), \(C_i\), and \(C_o\) for Group III are 0.39, 0.61, and 0.80, respectively. These values indicate that the aggregates have a subelliptical-subrounded-smooth shape. The mean values of 0.25, 0.72, and 0.94 indicate that loess columns have an elongated-subrounded-smooth shape. The aforementioned results show that all the structural blocks of loess, regardless of their size, are similar in shape. The blocks are elongated with a length-to-width ratio \((L/W)\) of approximately 2.6. The corners of the structural blocks are rounded or subrounded, and the surfaces of the blocks are smooth.

Rose diagrams were used in this study to examine the orientation distribution of loess structural blocks. The rose diagram was divided into nine zones, with each zone having a span of 10°, as shown in Fig. 7. The directional frequency \(F(\varepsilon)\) was calculated according to Table 2 by determining the number of structural blocks in each zone and then dividing it by the total number of blocks.

As shown in Fig. 7, the particles in Group I are mainly aligned in the sub-horizontal direction, with numerous particles falling within the range of 5°–50°. The particles in Group II appear to be evenly distributed over a wide range, but the directional frequency gradually increases with orientation angle, thereby indicating the relative dominance of vertical alignment. The structural blocks in Groups III–VI exhibit a concentration of orientation angles that is close to 90°, which indicates a subvertical or vertical alignment. Fig. 8 plots the overall mean orientation angle \(\varepsilon\) of structural blocks for each group and
indicates that large structural blocks are more aligned vertically than small blocks. Directional probability entropy ($H_m$) indicates the extent to which the orientations of the structural blocks are concentrated (Table 2). Its values are within the range from 0 to 1. If all the structural blocks being examined are evenly distributed, i.e., perfectly random distribution of orientation, then $H_m$ will be 1. By contrast, if all the structural blocks are aligned in the same direction, then the $H_m$ value will be 0. As shown in Fig. 9, the fragments (III), aggregates (IV), lumps (V), and columns (VI) have an $H_m$ that is less than 0.5, thereby showing a relatively concentrated alignment, whereas the other two groups (clay- and silt-sized particles) have a higher $H_m$, which indicates a relatively random distribution.

5. Discussion

5.1. Vertically piled soil particles and force chains in the Malan loess

During the accumulation of dust and the structural evolution of loess, various forces are involved in the packing of soil particles, such as van der Waals and electrostatic forces, hydrogeochemical reaction, dynamic water flow, and mechanical force due to gravity (Yu et al., 2003; Mao et al., 2014). Clay minerals in loess are mainly kaolinite, illite, montmorillonite, and chlorite (Galovic et al., 2006; Újvári et al., 2008). These layer-structured clay particles favor a horizontal or sub-horizontal arrangement during deposition (Li et al., 2013). Van der Waals and electrostatic forces dominate in packing particles smaller
### Group Distribution of Shape Parameters of Loess Structural Blocks

<table>
<thead>
<tr>
<th>Group</th>
<th>$\alpha$</th>
<th>$C_T$</th>
<th>$C_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td><img src="image1.png" alt="Graph I" /></td>
<td><img src="image2.png" alt="Graph II" /></td>
<td><img src="image3.png" alt="Graph III" /></td>
</tr>
<tr>
<td>II</td>
<td><img src="image4.png" alt="Graph IV" /></td>
<td><img src="image5.png" alt="Graph V" /></td>
<td><img src="image6.png" alt="Graph VI" /></td>
</tr>
<tr>
<td>III</td>
<td><img src="image7.png" alt="Graph VII" /></td>
<td><img src="image8.png" alt="Graph VIII" /></td>
<td><img src="image9.png" alt="Graph IX" /></td>
</tr>
<tr>
<td>IV</td>
<td><img src="image10.png" alt="Graph X" /></td>
<td><img src="image11.png" alt="Graph XI" /></td>
<td><img src="image12.png" alt="Graph XII" /></td>
</tr>
<tr>
<td>V</td>
<td><img src="image13.png" alt="Graph XIII" /></td>
<td><img src="image14.png" alt="Graph XIV" /></td>
<td><img src="image15.png" alt="Graph XV" /></td>
</tr>
<tr>
<td>VI</td>
<td><img src="image16.png" alt="Graph XVI" /></td>
<td><img src="image17.png" alt="Graph XVII" /></td>
<td><img src="image18.png" alt="Graph XVIII" /></td>
</tr>
</tbody>
</table>

**Fig. 6.** Statistic distribution of shape parameters of loess structural blocks in each group. (The abscissa of the subgraphs represents parameters in the column head, and the ordinate represents frequency percentage; $\mu$ – mean value; $\sigma$ – variance; $s$ – skewness.)

than 100 μm (Yu et al., 1997; Visser, 1989; Israelachvili, 1992) and generally result in a haphazard packing structure (Dijkstra et al., 1995). This is why the silt particles in the Malan loess tend to show a random alignment.

The hydrogeochemical reaction after the deposition of windblown dust generates secondary fine calcite. The calcite particles function as an adhesive that bonds clay particles to other larger particles (Zhang et al., 2013; Smalley and Marković, 2014) and cement these particles together to form aggregates. Zhang and Liu (2010) indicated that hydrogeochemical reaction in soil more likely occurs in the vertical direction because the driving forces (e.g., rainwater leaching and evaporation) for this reaction work vertically. This mechanism explains the phenomenon that aggregates in the Malan loess tend to exhibit a vertical or subvertical alignment.

Under overburden pressure by continuous dust accumulation, loess particles are pushed to come in contact preferentially in the vertical direction. This leads to the formation of force chains along the vertically piled loess particles, and the stronger connection of loess particles in vertical direction than in horizontal directions (Fig. 10a). More information about force chain in soils can be found in Majmudar and Behringer (2005) and Zhang et al. (2013).

We conducted five sets of ultrasonic tests on undisturbed the Malan loess collected from Yuci City, China. Each set had six specimens, which were prepared, from the same loess block, to be cubes measuring 200 mm × 200 mm × 200 mm. All specimens were tested at completely dry condition. Nine measurements were made for each of the X, Y and Z directions of the specimen, where Z stands for the vertical direction and X and Y are the horizontal directions. As shown in Fig. 11, the average wave velocities in the vertical (Z) direction are all greater than those in the horizontal directions. This indicates that loess is more compacted in the vertical direction, and the continuity of loess particles in the vertical direction is considerably better than that in the horizontal directions.

5.2. Pores and cracks in the Malan loess

The alignment of macropores between aggregates in the Malan loess was examined in this study. The SEM images with aggregates (Fig. 4-III) were digitized and imported into ArcGIS for buffer analysis. The buffering process scales up the loess particles, without changing their aspect ratios, to close the pores on SEM images. Consequently, the pores

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**Fig. 7.** Rose diagrams showing the frequency distribution of orientation angles of loess structural blocks for each group.

**Fig. 8.** Mean orientation angle (ε) of loess structural blocks for each group.

**Fig. 9.** Directional probability entropy of loess structural blocks in each group.

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are isolated and extracted. This process reduces pore size to a certain extent but retains shape and alignment. As shown in Fig. 12, the extracted macropores exhibit a subvertical or vertical alignment. This result is in good agreement with Chen (2006), which indicates a concentration of pore alignment within the range of 50°–60°. Li et al. (2018b) reconstructed and examined 3D macropore structure of the Malan loess by using computed tomography technology. They concluded that pores in the Malan loess display better connectivity in vertical direction than in horizontal directions and that the Malan loess is characterized with vertically aligned, thick and straight pipes (Fig. 10b).

The vertically aligned pipes/cracks in loess mainly include root holes (Beven and Germann, 1982; Gocke et al., 2014), worm holes (Lei, 1986; Botschek et al., 2002), leaching pipes (Lu et al., 2005) and tension cracks (Smalliey et al., 2016). During the formation of the Malan loess, the areas of LPC was mainly covered by desert steppe with herbage (Wen et al., 1982; Chen et al., 1996). The roots of herbage were thin and long, and extended vertically or subvertically in order to get water as the climate was typically dry (annual precipitation of about 200 mm) and cold (annual average temperature of less than 0 °C) (Liu, 1985). The holes were formed after the roots were dead and rotted away (Beven and Germann, 1982; Gocke et al., 2014). Worm holes in loess, with a diameter of 0.5 to 5 mm, were due to activities of worms (e.g., earthworms) and tardigvades (e.g., ants) (Lei, 1986). Worm holes are generally curved circular pipes and most of them, such as those dug by earthworms, exhibit vertical or subvertical alignment (Botschek et al., 2002).

After the accumulation of windblown dust, loess experiences a long period of structural evolution, called loessification (Smalliey et al., 2011). The functions of water and stress are believed to be the main forces that drive the loessification processes (Chamberlain and Gow, 1979; Vandenbygaart et al., 1999; Pires et al., 2008; Smalliey and Marković, 2014). Downward infiltration of gravity water into the vadose zone relocates small particles (Lu et al., 2005; Zhu, 2009; Huang, 2004) and dissolve soluble substances (Yu, 1990; Guo et al., 2008), leading to the formation of vertical or subvertical pipes in soil. On the other hand, desiccation during dry periods of the wetting-drying cycles has the potential to result in contraction, which in turn, leads to tensile fracturing (Li et al., 2014; Liu, 2016). Swelling–shrinkage due to seasonal and daily temperature fluctuations also results in tensile fracturing (Mao et al., 2014). Since vertical stress is generally greater than horizontal stress (ratio between them is about 2) in common soil strata, tensile fracturing caused by desiccation and swelling–shrinkage cycles more likely occurs horizontally (Dinka et al., 2013). This facilitates the formation of macro-scale vertically oriented cracks or pipes (Chamberlain and Gow, 1979; Messing and Jarvis; 1990). These
vertically aligned weak segments (cracks and pipes) provide paths for the later infiltration of water flow, which in turn, enlarges weak segments. The accumulation of snow water in weak segments and the subsequent freezing-thawing cycles work in the same manner to allow weak segments to further develop vertically.

The above functions produce a network of discontinuities in loess mass, and the network is characterized by a high density (population) of vertically aligned, thick and straight cracks/pipes (Fig. 10b).

5.3. The proposed “vertiloess” structure of the Malan loess

Clay and silt particles in the Malan loess comprise aggregates, whereas aggregates compose other bigger structural blocks. The results of this study show that all the structural blocks (from clay particles to columns) have a similar shape, i.e., they are elongated. These elongated structural blocks, except for the clay and silt particles, exhibit a vertical or subvertical alignment. The foregoing discussions on both structural blocks and pipes/cracks lead to a schematic diagram showing the structure of the Malan loess (Fig. 13), which is characterized by vertically aligned strong units coupled with vertically aligned weak segments. We propose this structure for the Malan loess, and denote it as “vertiloess” structure. This term is partially borrowed from the FAO (Food and Agriculture Organization of the United Nations) and USDA (United States Department of Agriculture) soil taxonomy, where “vertisol” is used to name soil in which deep vertical cracks, just as in loess, develop in drier seasons or years, although there is a relatively high content of expansive montmorillonite clay in vertisol.

The vertically aligned strong units and weak segments make loess an anisotropic geological material. On the one hand, the vertically aligned strong units are protected by the fabric interlocking mechanism as they are held by force chains inside them. The force chain prevents erosion and weathering in the horizontal direction. These mechanisms have been testified by Bruthans et al. (2014) with laboratory experiments and numerical simulation.

On the other hand, the vertically aligned weak segments minimize the horizontal connection or bonding among loess material. They provide potential planes for loess failures, which typically occur in peeling, toppling, falling and cracking-sliding collapse modes under gravity (Li et al., 2018b). These failures are characterized by small volume and shallow failure surface at deep angles. In addition, the vertiloess structure favors surface spalling of vertical loess pieces with small size of about tens or hundreds of cubic centimeters, due to raingrowth impact, flowing water, daily or seasonal temperature fluctuation, freezing-thawing and wetting-drying cycles. The above-mentioned failures gradually shape a loess landform, particularly along the boundaries of a loess platform, into columns.

6. Conclusions

Loess is an aeolian deposit that is widely distributed worldwide. Although loess has a loose structure, loess columns are popular as part of spectacular loess landforms and can stand stably for hundreds of years. The present study analyzed the shape and alignment of the Malan loess structural blocks with different sizes to gain insights into the formation of loess columns. The preceding discussions lead to the following main conclusions.

(1) The structural blocks of the Malan loess have similar shapes, regardless of their size. In 2D vision, these blocks are elongated and have a length-to-width ratio of approximately 2.6. The corners of structural blocks are rounded or subrounded, and block boundaries are smooth.

(2) The elongated structural blocks of the Malan loess differ in terms of alignment. Small blocks (clay- and silt-sized particles) demonstrate a haphazard distribution over a wide range of orientations, and large blocks (i.e., aggregates, fragments, lumps, and columns) exhibit a strong concentration in the vertical or subvertical alignment.

(3) The consistency of alignment of large structural blocks implies that loessification processes (i.e., hydrogeochemical reaction, dynamic water flow, tensile fracturing due to either temperature fluctuation or desiccation) introduce more vertical than horizontal discontinuities in the Malan loess.

(4) The vertically aligned strong units, which are composed of loess aggregates, fragments and lumps and held by force chain, and the vertically aligned weak segments, which are composed of cracks and pipes, make the Malan loess inhomogeneous and anisotropic. This anisotropic structure is named as vertiloess structure, which prevents horizontal erosion and favors spalling, peeling, toppling, falling and cracking-sliding of vertical loess pieces, thereby forming loess columns.

As 2D images exhibit certain limitation in obtaining the true shape and alignment of loess structural blocks, developing high-resolution 3D structural models using other techniques, such as CT scanning, turns to
be a demand. However, the preparation of small, undisturbed, but representative loess samples and the implementation of algorithms for 3D structure reconstruction remain considerable challenges.

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