Earthquake Hazards in The Loess Plateau, China and It Prevention

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1. Introduction of the loess plateau
2. Seismic landslides
3. Liquefaction
4. Seismic subsidence
5. Loess flow under the coupling effect of earthquake and rainfall
6. Conclusions
CONTENTS

1. Introduction of the loess plateau
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Distribution of Loess in China

The Loess Plateau covers the area of 440,000 km², 4.6% of the whole territory of China.
Thickness of Loess in the Plateau

The loess thickness in Loess Plateau

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![Map showing the thickness of loess in the Loess Plateau](image)

Legend:
- **>200m**
- **200 ~ 100m**
- **100 ~ 50m**
- **<50m**
- **<30m**
The Typical Landforms in the Loess Plateau of China

“Yuan”, a wide plain with abruptly descending edges.
The Typical Landforms in the Loess Plateau of China

“Liang”, the long ridge of loess hills.
The Typical Landforms in the Loess Plateau of China

“Mao”, the round mound of loess deposit.
The Typical Landforms in the Loess Plateau of China

The river valleys and terraces
The typical profile of Loess in China
The gradation curve of loess compared with other soils
Loess has high collapsibility and dynamic vulnerability due to its porous microstructure with weak cohesion.

Void Ratio: 0.879-1.293
1. Introduction on Loess Plateau of China

Active Faults and Seismicity in Loess Plateau

Ms>=8: 6次
Ms>=7: 22次
Ms>=6: 52次

Fig. Regional Tectonic And Epicentres Of Large Earthquakes (Ms >= 7) In Loess Region Of West China
1. Introduction on Loess Plateau of China

Seismicity:
In years B.C. 78 ~ 2005 Sept. 30, but the data for 3.0~3.9 and 4.0~4.9 is in the recent 35 years.
In history, 1.4 million people were killed by earthquakes in the loess plateau areas. Except the poor seismic performance of houses, earthquake induced landslides, liquefaction, seismic subsidence and site effect are the major reason for the enormous casualties.
CONTENTS

1. Introduction of the loess plateau
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3. Liquefaction
4. Seismic subsidence
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6. Conclusions
(1) Distribution and Characteristics of Seismically Induced Loess Landslides

Distribution of seismically induced landslides caused by historical earthquakes in years between 1500 and 1949 in Loess Plateau.
Distribution of Landslides induced by the Tianshui 8.0 Earthquake in 1654 (600km²)
Distribution of landslides induced by The Tongwei 7.5 Earthquake in 1718 (800km²)
Distribution of seismic landslides induced by the Gulang 8.0 earthquake in 1927 (1000km²).
The 1920 Haiyuan 8.5 earthquake Induced three areas of dense landslides (5600km²).
Densely distribution of landslides induced by The 1920 Haiyuan 8.5 earthquake Landslides
Bacterial lake formed by loess Landslides
Sliding soil flowed out of the sliding bed.

SunJiaGou landslides with Sliding area: 1500m × 850m
Loess landslides have no a dominant sliding direction
Liquefaction of loess triggered soil flow with 2km in ShiBeiYuan induced by the Haiyuan 8.5 earthquake in 1920.
A loess landslide caused by the Yongdeng 5.8 Earthquake in 1995, which killed 6 people.
Characteristics of Seismically Induced Loess Landslides

• Gentle slope angle (5-20 degree)
• Low water content (10-20%)
• Stream-like sliding
• Landslides formed in Loess Liang and Mao
• Liquefaction induced Sliding flow developed in loess Yuan
• Sliding surface in the late Pleistocene deposit (Q₃) or the boundary of Q₃ and Q₂
• Densely distributed along active faults and slopes of Valley.
### The Scales of Landslides induced by the Haiyuan 8.5 Earthquake in 1920

<table>
<thead>
<tr>
<th>Size of Landslides</th>
<th>Small</th>
<th>Medium</th>
<th>Large</th>
<th>Very Large</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume (m³)</td>
<td>&lt;30000</td>
<td>30000-500000</td>
<td>500000-3M</td>
<td>&gt;3M</td>
</tr>
<tr>
<td>Number*</td>
<td>6</td>
<td>29</td>
<td>22</td>
<td>5</td>
</tr>
<tr>
<td>Percentage</td>
<td>9.68</td>
<td>46.78</td>
<td>35.48</td>
<td>8.06</td>
</tr>
</tbody>
</table>

* 62: Number of investigated landslides induced by the Haiyuan 8.5 Earthquake in 1920
The Influence of Seismic Intensity on Distribution of Landslides in Loess Plateau

- VI degree: Collapse;
- VII degree: The minimum intensity for triggering landslides;
- VIII degree: Dense distribution;
- \( \geq IX \) degree: Whole land feature could be changed.
(2) **Prediction** and Zonation of Seismically Induced Loess Landslides

A seismic landslide in Huihuichuan, as an example for back analysis
Seismic loading used in the test of dynamic strength
For the analysis of Huihuichuan landslide

Physical parameters of loess in the site of Huihuichuan landslide

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Weight Unit (kN/m³)</th>
<th>Water Content(%)</th>
<th>Void Ratio</th>
<th>Plastic Limit</th>
<th>Plastic Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q89-3</td>
<td>13.965</td>
<td>18.98</td>
<td>1.038</td>
<td>21.4</td>
<td>10.8</td>
</tr>
</tbody>
</table>
Strength test results on loess samples in Huihuichuan

(a) Dynamic strength

$G89-3$
$C_d=16.862kPa$
$\varphi_d=23^\circ$

(b) Static strength

$G89-3$ 西吉原状黄土
$C=44.1kPa$
$\varphi=17.2^\circ$
\[ K_d = \frac{\sum W \cos \alpha - \frac{\alpha_{\text{max}}}{g} \cdot \sum W \sin \alpha}{\sum W \sin \alpha + \frac{\alpha_{\text{max}}}{g} \sum W \cos \alpha} \tan \varphi + C \sum 1 \]
Safety factor, $K_d$, vs PGA from the back analysis.
(2) Prediction and **Zonation** Methods of Seismically Induced Loess Landslides

- Empirical Zonation Method
- GIS-Based Zonation Method
*Statistic analysis on MD is based on around 50 earthquakes.
The empirical formula of MD for seismically induced landslides in the Loess Plateau

<table>
<thead>
<tr>
<th>Area</th>
<th>MDE /R</th>
<th>MDSF /R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense area</td>
<td>log $D_e = 12.82 \log M_s - 9.508; /0.83$</td>
<td>log $D_f = 16.13 \log M_s - 12.624; /0.83$</td>
</tr>
<tr>
<td>Scatter area</td>
<td>log $D_e = 9.901 \log M_s - 6.332; /0.91$</td>
<td>log $D_f = 10.53 \log M_s - 7.039; /0.91$</td>
</tr>
</tbody>
</table>

*Based on the potential earthquake epicenters or seismic faults, the potential areas of seismic landslides could be figured out according to the formulas.*
3. Prediction and Zonation of Seismically Induced Loess Landslides

### MDC(S)E and MDC(S)F for Seismic Landslides

<table>
<thead>
<tr>
<th>Magnitude (Ms)</th>
<th>MD (km)</th>
<th>MD (km)</th>
<th>MD (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MDCE</td>
<td>MDSE</td>
<td>MDCF</td>
</tr>
<tr>
<td>5.5</td>
<td>—</td>
<td>10</td>
<td>—</td>
</tr>
<tr>
<td>6.0</td>
<td>—</td>
<td>24</td>
<td>—</td>
</tr>
<tr>
<td>6.5</td>
<td>8</td>
<td>52</td>
<td>3</td>
</tr>
<tr>
<td>7.0</td>
<td>21</td>
<td>108</td>
<td>10</td>
</tr>
<tr>
<td>7.5</td>
<td>51</td>
<td>215</td>
<td>31</td>
</tr>
<tr>
<td>8.0</td>
<td>117</td>
<td>263</td>
<td>70</td>
</tr>
<tr>
<td>8.5</td>
<td>140</td>
<td>310</td>
<td>105</td>
</tr>
</tbody>
</table>
Reference values of MI and MPGA of triggering landslides

<table>
<thead>
<tr>
<th>Type of Disasters</th>
<th>MI (degree)</th>
<th>MPGA (gal=cm/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seismically Induced Landslides</td>
<td>Ⅶ</td>
<td>170</td>
</tr>
</tbody>
</table>

Based on the “Zonation Map of Seismic Ground Motion of China”, using the reference values of MI and MPGA of triggering landslides, the zonation maps of seismic landslide in the Loess Plateau could be outlined approximately.
GIS-based **Zonation** of Seismically Induced Loess Landslides

The comparative matrix of factors impacting landslide

<table>
<thead>
<tr>
<th>Seismic Acceleration</th>
<th>Morphology type</th>
<th>Stratum</th>
<th>Precipitation</th>
<th>Slope Angle</th>
<th>Natural Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seismic Acceleration</td>
<td>1</td>
<td>2</td>
<td>7</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Morphology type</td>
<td>1/2</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Stratum</td>
<td>1/7</td>
<td>1/5</td>
<td>1</td>
<td>1/3</td>
<td>1/3</td>
</tr>
<tr>
<td>Precipitation</td>
<td>1/5</td>
<td>1/5</td>
<td>3</td>
<td>1</td>
<td>1/4</td>
</tr>
<tr>
<td>Slope Angle</td>
<td>1/5</td>
<td>1/3</td>
<td>3</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Natural Density</td>
<td>1/8</td>
<td>1/7</td>
<td>1/2</td>
<td>1/3</td>
<td>1/6</td>
</tr>
</tbody>
</table>
Influence factors of seismic landslide in Loess Plateau for the GIS-based zonation method

PGA distribution with probability of exceedance, 63.5%, 10%, 2% in 50 years
Landslide zonation map for Loess Plateau
( probability of exceedance:63.5% in 50 years)
Landslide zonation map of Loess Plateau (probability of exceedance: 10% in 50 years)
Zonation map of Seismically induced Landslides for the Loess Plateau (PE: 2% in 50 years) with historical seismic landslides distribution
CONTENTS

1. Introduction of the loess plateau
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3. Liquefaction
4. Seismic subsidence
5. Loess flow under the coupling effect of earthquake and rainfall
6. Conclusions
The Site of Loess Liquefaction in Shibeiyuan Village, Ningxia Hui Autonomas Region, induced by the 1920 Haiyuan 8.5 Earthquake
New Madrid Earthquake, 1811-1812
A 5.5 Earthquake triggered mudflow buried a village and killed 274 people in Tajikistan in 1989.
Three typical deposit (Q3) of loess liquefaction in China, US, and Tajik
(b) Number of Cycles vs. Deviatoric Stress

(a) Number of Cycles vs. Excess Pore Pressure

(c) Number of Cycles vs. Axial Strain
(b) Number of Cycles vs. Deviatoric Stress

(c) Number of Cycles vs. Excess Pore Pressure

(c) Number of Cycles vs. Axial Strain
(a) Number of Cycles vs. Excess Pore Pressure & Axial Strain
$\sigma'_3 = 130 \text{ kPa}$

Back Pressure = 340 kPa

- $N_r = 62, \sigma_d = 15 \text{ kPa}$
- $N_r = 34, \sigma_d = 20 \text{ kPa}$
- $N_r = 12, \sigma_d = 25 \text{ kPa}$

Cycles Ratio vs. Axial Strain
For Undisturbed Saturated Saturated Loess
Laboratory Criteria of Loess Liquefaction

a. Sample after liquefaction test

b. Microstructure feature after liquefaction (×100)
Laboratory Criteria

• Based on the study of the behavior of the undisturbed and remolded loess, the criteria for recognizing liquefaction are given:

1) Under the isotropic consolidation,

\[ \varepsilon_d \geq 3\% \quad \text{and} \quad \frac{u_d}{u_f} \geq 0.4 \]

or

\[ \frac{u_d}{u_f} = 1 \]
(2) Under the anisotropic consolidation,

\[ \varepsilon_d \geq 3\% \quad \text{and} \quad \frac{u^d}{u_f} \geq 0.2 \]

- The air-filled small pores in loess cannot be fully saturated. When the loess structure collapses, water fills these pores, which prevents further development of pore pressure.

- The liquefaction of loess usually leads to rapid development of residual strain, which easily induces ground failure or mudflow.
Preliminary evaluation of loess liquefaction

• If the geological time of loess is during or older than middle period of Pleistocene in Quaternary (Q₂), loess liquefaction can be neglected under seismic intensity of 7 degree (0.15g) and 8 degree (0.20g,0.30g) . (The same as national code.)

• When the clay content of loess is respectively not less than 12,15 and 18 for seismic intensity of 7, 8 and 9 degree, loess liquefaction can be neglected.

• (clay content is raised by 2% for all seismic intensities comparing with national code, because loess with liquefaction potential usually has a higher clay content than clayed silt.)
SPT value of different kinds of saturated soil

- Loess
- Sand
- Gravel
- Cobble
## Average SPT values for different soils

<table>
<thead>
<tr>
<th>Soils</th>
<th>Minim SPT</th>
<th>Maximum SPT</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loess</td>
<td>1.8</td>
<td>12</td>
<td>6.3</td>
</tr>
<tr>
<td>Sand</td>
<td>10</td>
<td>21</td>
<td>13.1</td>
</tr>
<tr>
<td>Gravel</td>
<td>20</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>Cobble</td>
<td>39</td>
<td>55</td>
<td>47.4</td>
</tr>
</tbody>
</table>
The detailed evaluation method of sand liquefaction

\[ N_{cr} = N_0 \beta \left[ \ln(0.6d_s + 1.5) - 0.1d_w \right] \sqrt{3 / \rho_c} \]

- \( N_{cr} \): Critical SPT value for liquefaction
- \( N_0 \): Reference SPT value (See the following table)
- \( d_s \): Depth of saturated soil layer (m)
- \( d_w \): Underground water table (m)
- \( \rho_c \): Clay content, assign 3 if it is less than 3
- \( \beta \): Site adjustment parameter, ranges from 0.80 to 1.05 for site with different characteristic period.

<table>
<thead>
<tr>
<th>Design PGA (g)</th>
<th>0.1</th>
<th>0.15</th>
<th>0.20</th>
<th>0.30</th>
<th>0.40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference SPT value</td>
<td>7</td>
<td>10</td>
<td>12</td>
<td>16</td>
<td>19</td>
</tr>
</tbody>
</table>

If \( N < N_{cr} \), Liquefiable
If \( N > N_{cr} \), non-liquefiable
Modification of SPT value for Loess liquefaction evaluation

- The detailed evaluation method of sand liquefaction is adopted.
- The reference SPT value, $N_0$, of loess is modified to less than sand to reflect the fact that saturated loess has lower SPT value compared with sand. This avoids exaggeration of loess liquefaction during the detailed evaluation.

<table>
<thead>
<tr>
<th>Design PGA (g)</th>
<th>0.1</th>
<th>0.15</th>
<th>0.20</th>
<th>0.30</th>
<th>0.40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference SPT value</td>
<td>6</td>
<td>8</td>
<td>9</td>
<td>11</td>
<td>13</td>
</tr>
</tbody>
</table>
Liquefaction index Versus liquefaction grades

**Liquefaction Index**

\[ I_{lE} = \sum_{i=1}^{n} \left[ 1 - \frac{N_i}{N_{cri}} \right] d_i W_i \]

**SPT of layer i**

**Thickness of layer i**

**Weight factor of depth**

\[ W_i = \begin{cases} 10 & (d_s < 5\text{m}) \\ \frac{10}{3} \cdot d_s - \frac{20}{3} & (5 < d_s \leq 20) \end{cases} \]

<table>
<thead>
<tr>
<th>Liquefaction grade</th>
<th>Slight</th>
<th>Moderate</th>
<th>Severe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquefaction Index ((I_{lE}))</td>
<td>0 &lt; (I_{lE}) (\leq 6)</td>
<td>6 &lt; (I_{lE}) (\leq 18)</td>
<td>(I_{lE} &gt; 18)</td>
</tr>
</tbody>
</table>
Zonation of Loess liquefaction

• Zonation maps of loess liquefaction potential were respectively compiled for seismic hazards with exceeding probabilities of 10% and 2% within 50 years.

• The liquefaction potential zonation is mainly based on ground water table, plastic index and PGA. In terms of performance based seismic design, the potential of loess liquefaction is evaluated with the following four grades:
  non-liquefaction,
  slight liquefaction,
  moderate liquefaction
  serious liquefaction.
Loess liquefaction potential map

Loess liquefaction map under exceeding probability of 10% within 50 years for Lanzhou urban area

Loess liquefaction map under exceeding probability of 2% within 50 years for Lanzhou urban area
Loess liquefaction Treatment for certain class of buildings

<table>
<thead>
<tr>
<th>Liquefaction grade</th>
<th>Slight</th>
<th>Moderate</th>
<th>Severe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquefaction Index ($I_{le}$)</td>
<td>$0 &lt; I_{le} \leq 6$</td>
<td>$6 &lt; I_{le} \leq 18$</td>
<td>$I_{le} &gt; 18$</td>
</tr>
<tr>
<td>B level heights high-rising 2$^{nd}$ Class buildings</td>
<td>No treatment</td>
<td>Pile foundation adopt seismic resistance measures</td>
<td>1) Pile foundation needs pre-liquefaction and post-liquefaction bearing capacity and deformation calculation</td>
</tr>
<tr>
<td>High-rising 3$^{rd}$ Class buildings with heights larger than B level</td>
<td></td>
<td></td>
<td>2) Pile foundation adopts seismic resistance measures</td>
</tr>
<tr>
<td>High-span high-rising or very important buildings</td>
<td></td>
<td></td>
<td>3) Ground treatment to eliminate liquefaction</td>
</tr>
</tbody>
</table>
CONTENTS

1. Introduction of the loess plateau
2. Seismic landslides
3. Liquefaction
4. Seismic subsidence
5. Loess flow under the coupling effect of earthquake and rainfall
6. Conclusions
The drum building settled for more than 1m in Weinan City, China within the region of X degree intensity caused the Huaxian 8.0 earthquake in 1556.
A seismic subsidence of 20-40cm in a region of VIII degree intensity caused by the Yongdeng 5.8 earthquake in 1995.
Seismic Subsidence in Gansu Province (Qingshui: VI degree Intensity region) Induced by Wenchuan Ms 8.0 Earthquake in 2008
Distribution ratio of seismic subsidence in different intensity zones

IX and above: 43%
VIII: 30%
VII: 23%
VI: 4%
The macroscopic characteristics of seismic subsidence in unsaturated loess site

- Seismic subsidence occurred in MaLan (Q₃) and Holocene loess (Q₄) deposit.
- In some Loess Yuans, cracking and fissures could be found everywhere caused by inhomogeneous seismic subsidence.
- Step-like collapse and deformation on Loess Liang were caused by seismic subsidence during the Yongdeng 5.8 earthquake and the Wenchuan 8.0 earthquake.
SEISMIC SUBSIDENCE:
A field experiment, trying to prove its existing or facticity, and also to know seismic subsidence influencing negative skin friction on pile
SEISMIC SUBSIDENCE:
The ground motion simulated by a short delay blasting (30 explosive holes)
SEISMIC SUBSIDENCE:
30 explosive holes: 2 explosives as 1 blasting and delay 15 times, but 6 events no explosion, resulting in effective duration 3.23-5.67s, less than the design about 9s)

Try to understand: Seismic Subsidence and its effect of Negative Skin Friction on Pile, especially their developing features in a real loess field
The first one (top) and the ninth one

No explosion
Contour map of site seismic subsidence

8 days after the test
Negative friction resistance of pile foundation

![Graph showing the negative friction resistance of pile foundation over varying depths. The graph plots friction resistance in kPa against depth in meters, with different lines representing various time intervals and data sets labeled with identifiers such as Start0sec, S14sec, After9min, A1h29min, A2h59min, and A091219 to A092119.](image)
The critical dry density of the loess depression is 1.63 g/cm³ under the action of the seismic consolidation stress of 200 kPa and the seismic intensity not exceeding the intensity of IX.

<table>
<thead>
<tr>
<th>N</th>
<th>Fitting formula</th>
<th>correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>$\varepsilon_r = 32.86 - 19.49 \rho_d$</td>
<td>0.996</td>
</tr>
<tr>
<td>20</td>
<td>$\varepsilon_r = 39.38 - 23.40 \rho_d$</td>
<td>0.996</td>
</tr>
<tr>
<td>30</td>
<td>$\varepsilon_r = 42.46 - 25.23 \rho_d$</td>
<td>0.995</td>
</tr>
<tr>
<td>40</td>
<td>$\varepsilon_r = 45.13 - 26.82 \rho_d$</td>
<td>0.995</td>
</tr>
<tr>
<td>50</td>
<td>$\varepsilon_r = 46.90 - 27.87 \rho_d$</td>
<td>0.994</td>
</tr>
<tr>
<td>60</td>
<td>$\varepsilon_r = 48.16 - 28.62 \rho_d$</td>
<td>0.995</td>
</tr>
</tbody>
</table>
According to the criterion of segregation loess $\varepsilon_p = 0.015$, it can be seen that the minimum porosity ratio of loess is 0.8.
Comparison of subsidence curves under different water content

$\varepsilon_p = 1.5\%$

Boundary water content
When the shear wave velocity of the loess is greater than 380 m/s, the loess is not sagging.

\[
\varepsilon_p' = 74.391 - 0.920V_s + 0.350\sigma_d - 0.002V_s\sigma_d + 0.0028V_s^2 + 0.00024\sigma_d^2 \quad (r=0.95)
\]
Estimation model of residual strain of loess

\[ \varepsilon = \frac{1}{e_i + 1} \left( \left( 1 + \ln(N) \right) \times 1.3 \gamma zr_d \frac{a_{\text{max}}}{g} \right)^b \frac{C + \sigma_c \tan \varphi}{g} \]

This formula is more complete than the static condition of the Duncan-Zhang model in reflecting the dynamic deformation of the loess.
Zoning map of loess seismic subsidence (exceedance probability in 50 years is 2%)
Zoning map of loess seismic subsidence (exceedance probability in 50 years is 10%)
Zoning map of loess seismic subsidence (exceedance probability in 50 years is 63%)
CONTENTS

1. Introduction of the loess plateau
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3. Liquefaction
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6. Conclusions
The Coupling Effect

Earthquake + Rainfall / Underground Water

↓

Liquefaction mudflow
Loess liquefaction in the Shibei tableland
(HaiYuan Ms 8.5 Earthquake, 1920)
Continuous rainfall in the day before the Minxian-Zhangxian 6.6 earthquake in 2013.
Liquefaction triggered mudflows in Yongguang Village induced by the Minxian-Zhangxian Ms6.6 Earthquake in 2013

VIII Zone,
Max. sliding distance: 1.0km (left one)
(1) Influence of Water Content on Loess Strength

Table 1 – Physical parameters of loess specimens

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>ρ (g/cm³)</th>
<th>ρ_d (g/cm³)</th>
<th>ω (%)</th>
<th>PL (%)</th>
<th>PI</th>
<th>Grain composition (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Clay (&lt; 0.005mm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Silt (0.005~0.075mm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Sand (&gt; 0.075mm)</td>
</tr>
<tr>
<td>5</td>
<td>1.34</td>
<td>1.28</td>
<td>5.04</td>
<td>17.2</td>
<td>7.3</td>
<td>14.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>68.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>17.3</td>
</tr>
<tr>
<td>10</td>
<td>1.36</td>
<td>1.30</td>
<td>4.25</td>
<td>18.5</td>
<td>7.5</td>
<td>17.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>66.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>16.4</td>
</tr>
</tbody>
</table>
Static and dynamic triaxial tests were performed on loess specimens with different water contents.
Both cohesion, \( c \), and internal friction angle, \( \phi \), decrease dramatically with increasing of water content.

**Fig. 2** – Cohesion (left) and internal friction angle (right) respectively versus water content

\[
y = -19.349 \ln(x) + 85.947 \quad R^2 = 0.8137
\]

\[
y = -14.939 \ln(x) + 65.573 \quad R^2 = 0.9889
\]

\[
y = -0.7352x + 43.899 \quad R^2 = 0.9921
\]

\[
y = -0.769x + 47.71 \quad R^2 = 0.8448
\]
Both dynamic cohesion, $c_d$, and dynamic internal friction angle, $\phi_d$, decrease dramatically with increasing of water content.
A field artificial rainfall tests on a loess slope with a gradient of 20º in Lanzhou New District.
The loess slope site after the field raining test
The Max. rainfall infiltration depth: 2.5m

The raining water made the slope surface layer saturated.
(2) Shaking Table Tests with different rainfalls and peak accelerations were performed.

Table size: 4m × 6m, Max. load: 25 ton, horizontal and vertical running directions, and driven by 24 servo motors. Max. acceleration, velocity and displacement: 1.7 g, 1.2 m/s and ±50 cm. The table effective frequency range: 0.1 Hz ~ 70 Hz.
The soil parameters of shaking table model

<table>
<thead>
<tr>
<th>Physical Indexes</th>
<th>Similarity ratio</th>
<th>Actual value</th>
<th>Target value</th>
<th>Test Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>w (%)</td>
<td>1</td>
<td>4.1~5.6</td>
<td>4.1~5.6</td>
<td>6</td>
</tr>
<tr>
<td>$\rho/ (10^3\text{kg/m}^3)$</td>
<td>1</td>
<td>1.31~1.34</td>
<td>1.31~1.34</td>
<td>1.32</td>
</tr>
<tr>
<td>C (kPa)</td>
<td>10</td>
<td>43.2~50.2</td>
<td>4.3~5</td>
<td>9</td>
</tr>
<tr>
<td>$\phi$ (°)</td>
<td>1</td>
<td>35~37</td>
<td>35~37</td>
<td>33</td>
</tr>
</tbody>
</table>
The time history of ground acceleration and its spectrum of the Minxian-Zhangxian Ms6.6 earthquake in 2013 was applied in the tests.
## Loading conditions

<table>
<thead>
<tr>
<th>Serial number</th>
<th>Intensity</th>
<th>Input wave</th>
<th>Peak acceleration</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>VI (0.05g)</td>
<td>Sine wave (constant amplitude, 3~50Hz)</td>
<td>50gal</td>
<td>Horizontal</td>
</tr>
<tr>
<td>2</td>
<td>VII (0.1g)</td>
<td>The original/compressional Minxian wave</td>
<td>100gal</td>
<td>Horizontal</td>
</tr>
<tr>
<td>3</td>
<td>VIII (0.2g)</td>
<td>The original/compressional Minxian wave</td>
<td>200gal</td>
<td>Horizontal</td>
</tr>
<tr>
<td>4</td>
<td>IX (0.4g)</td>
<td>The original/compressional Minxian wave</td>
<td>400gal</td>
<td>Horizontal</td>
</tr>
<tr>
<td>5</td>
<td>IX (0.6g)</td>
<td>The original/compressional Minxian wave</td>
<td>600gal</td>
<td>Horizontal</td>
</tr>
<tr>
<td>6</td>
<td>X (0.7g)</td>
<td>The original/compressional Minxian wave</td>
<td>700gal</td>
<td>Horizontal</td>
</tr>
<tr>
<td>7</td>
<td>XI (1g)</td>
<td>The original/compressional Minxian wave</td>
<td>1000gal</td>
<td>Horizontal</td>
</tr>
</tbody>
</table>
10mm rainfall shaking table test

700 gal: Tension crack failure, seismic subsidence of slope top;
1000 gal: slip cracking, seismic subsidence, cracks spread all over.

The effect of earthquakes:
large pore collapse - dramatically residual deformation (seismic subsidence)-sliding
Pore pressures increased with increasing of PGA, but no obvious residual pore pressure to develop.

Variation of pore pressure of the slope model in the case of 10mm rainfall
100mm rainfall shaking table tests

400gal: pore pressure rises, but the soil is not liquefied.
100mm rainfall shaking table tests

600gal: pore pressure rapidly increased, liquefaction was triggered on the top of the slope. The slope shoulder began to slide along the surface of the slope.
100mm rainfall shaking table tests

650gal: liquefaction-induced mudflow on the slope slid down.
Variation of pore pressure in the loess slope in the shaking table tests after 100 mm rainfall.
PGA amplification effect

1. Amplification effect with elevation.
   (especially \( h > \frac{2}{3}H \))

2. Amplification effect with rainfall.

3. Amplification effect with shaking intensity.
   When the model appears unstable failure, the amplification effect attenuates rapidly
Stability Evaluation of Loess Slope Based on Shaking Table Test

The Spectrums of transfer function of slope shoulder show that when the slope models become unstable, the spectral peak values of their transfer functions are around or lower than 2.0. This common failure value may provide a method to determine the critical peak acceleration of inducing the slope failure.
The curves of the peak value of spectral amplitude versus PGA of dynamic loading with different rainfalls can be figured out.

The critical PGA of a slope failure under different rainfall conditions may be predicted by the curves of TFS peak values versus PGA based on the shaking table tests.

**Critical instability acceleration:** 0.46g (rainfall 100mm); 0.76g (rainfall 10mm) 0.89g(rainfall 0mm), Considering similarity ratio of 0.656, the critical PGA should be 0.3g, 0.5g and 0.58g for the real slope.
The critical PGA causing loess slope completely failure at different rainfall conditions

The critical acceleration of instable slopes and failure modes at different rainfall conditions

The critical PGA causing loess slope completely failure at different rainfall conditions
Stability Evaluation of Loess Slope Based on Shaking Table Test

The equivalent shear wave velocity $V_s$ of slope soil can be obtained by the natural frequency.

Let $V_{scr}$ represent the critical state shear wave velocity of the slope, $V_s / V_{scr}$ is for the strength reserve of the soil relative to the critical instability.

Let $a_{cr}$ be the critical instability acceleration of the slope, $a_{cr} / a$ represents the safety level under the effect of the earthquake, which is less than 1 may characterize the slope instability.

And then set the stability coefficient of the slope in the critical state be 1, the stability coefficient of the slope under the effect of an earthquake can be expressed by the following formula.

$$S_f = \frac{\left( a_{cr} / a \right)}{\left( V_s / V_{scr} \right)}$$
Safety factors of loess slopes can be evaluated based on shaking table test results with different rainfalls and ground motions.

Based on safety considerations, when the $S_f = 1.2$, the critical acceleration value is 0.3g, 0.5g and 0.64g when the rainfall is 100mm, 10mm and 0mm.

\begin{align*}
S_{f10mm} &= -283.59a^5 + 730.02a^4 - 736.25a^3 + 368a^2 - 94.99a + 11.682 \\
S_{f100mm} &= -125.87a^3 + 128.97a^2 - 45.47a + 6.609
\end{align*}
## (3) Performance-based design method

### Fortification Category

<table>
<thead>
<tr>
<th>Fortification Category</th>
<th>Definition</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Special Fortification</td>
<td>The special infrastructures and facilities involving in the state public safety and possibly inducing particularly serious disasters</td>
<td>A</td>
</tr>
<tr>
<td>Key Fortification</td>
<td>Lifeline engineering facilities of which functions can not be interrupted by earthquakes and rainfalls.</td>
<td>B</td>
</tr>
<tr>
<td>Standard fortification</td>
<td>The buildings and facilities expecting A and B.</td>
<td>C</td>
</tr>
</tbody>
</table>
# Classification of Performance Requirements under the Coupling Effect

<table>
<thead>
<tr>
<th>Classification</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>PR-1 (I)</td>
<td>The facilities can avoid influence of liquefaction-triggered landslides and mudflow; Or the facilities can not be damaged and their functions can be kept without any repair.</td>
</tr>
<tr>
<td>PR-2 (II)</td>
<td>The facilities can avoid influence of landslides under the coupling effect; or the facilities may be slightly damaged but their functions can be recovered by repair in a short time.</td>
</tr>
<tr>
<td>PR-3 (III)</td>
<td>The main structures have no serious damage and can be recovered by repair.</td>
</tr>
</tbody>
</table>
# Fortification Target

<table>
<thead>
<tr>
<th>Fortification category</th>
<th>Frequent ground motion and rainfall</th>
<th>Basis ground motion and rainfall</th>
<th>Rare ground motion and rainfall</th>
<th>Very rare ground motion and rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Special Fortification (A)</td>
<td>I</td>
<td>I</td>
<td>II</td>
<td>III</td>
</tr>
<tr>
<td>Key Fortification (B)</td>
<td>I</td>
<td>II</td>
<td>III</td>
<td>_</td>
</tr>
<tr>
<td>Standard Fortification (C)</td>
<td>I</td>
<td>II</td>
<td>III</td>
<td>_</td>
</tr>
</tbody>
</table>
## Definition of Fortification Level

<table>
<thead>
<tr>
<th>Fortification level</th>
<th>Ground motion (Probability of exceedance)</th>
<th>Rainfall (Probability of exceedance / reoccurrence period)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequent</td>
<td>63% in 50 years</td>
<td>10% in 1 year / 10 years</td>
</tr>
<tr>
<td>Basis</td>
<td>10% in 50 years</td>
<td>5% in 1 year / 20 years</td>
</tr>
<tr>
<td>Rare</td>
<td>2% in 50 years</td>
<td>2% in 1 year / 50 years</td>
</tr>
<tr>
<td>Very rare</td>
<td>0.01% in 1 year</td>
<td>1% in 1 year / 100 years</td>
</tr>
</tbody>
</table>
Evaluation of Safety factors of a loess slope with different PGAs and rainfalls

\[
S_{f_{0\text{mm}}} = -200.86a^5 + 587.09a^4 - 667.92a^3 + 373.23a^2 - 105.77a + 14.163
\]

\[
S_{f_{10\text{mm}}} = -283.59a^5 + 730.02a^4 - 736.25a^3 + 368a^2 - 94.99a + 11.682
\]

\[
S_{f_{100\text{mm}}} = -125.87a^3 + 128.97a^2 - 45.47a + 6.609
\]
CONTENTS

1. Introduction of the loess plateau
2. Seismic landslides
3. Liquefaction
4. Seismic subsidence
5. Loess flow under the coupling effect of earthquake and rainfall
6. Conclusions
5. Conclusions—1/3

(1) Landslide, subsidence and liquefaction are three major geotechnical earthquake disasters in the Loess Plateau, which may be induced under the effect of VII degree intensity and have a high risk of becoming catastrophic under a seismic intensity equal to or stronger than VIII degree.

(2) Engineering projects should be set back from the landslide affected areas. Site effect also should be considered in seismic design of loess slopes.
(3) Liquefaction potential of Loess may be evaluated by both physical parameters preliminarily and SPT tests in details.

(4) Seismic subsidence of loess ground may be eliminated by compaction treatment, which should be treated with collapsibility of loess together in one time.
5. Conclusions—3/3

(5) Under the coupling effect of earthquakes and rainfalls, loess slopes have different failure types, tensile fissures, inhomogeneous subsidence and cracks, landslides, and liquefaction-triggered mud flow or soil flow.

(6) The performance-based seismic design method of loess slopes may take into account of the coupling effect of earthquakes and rainfalls with different fortification levels.
Thank you
For your attention!