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RECENT PROGRESSES IN LOESS EARTHQUAKE ENGINEERING AND CHINA-EU COOPERATION

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ABSTRACT

Loess is widely distributed in the world. The Loess Plateau in China is a region with the biggest area, thickness and most complicated topography of loess deposit in the world, where is also strong earthquake-prone region. In history, more than 1.4 million people were killed by earthquakes in the Loess Plateau area. Seismic amplification effects of loess deposit, seismic landslides, liquefaction-induced soil flow and seismic subsidence are the main cause of enormous casualties except poor seismic capability of houses. In this paper, recent progresses in site effect, seismic landslides, liquefaction and seismic subsidence of loess deposit with different landforms as well as their applications in seismic design code and risk management are introduced. The present cooperative research achievements between China and EU are summarized and the bilateral future collaboration is proposed.

Keywords: Loess Earthquake Engineering; Site effect; Landslides;Liquefaction; Subsidence

1. INTRODUCTION

The Loess Plateau is the most widely distributed area with the thickest loess deposit and the most complicated topography in the world, where is also a strong earthquake-prone region. Loess has porous microstructure and weak cementation, which leads to its strong water sensitivity and seismic vulnerability. The historical strong earthquakes caused many changes in the mountains and rivers by landslides, liquefaction-induced soil flow and subsidence, killing over 1.4 million people and making countless property loss. Among the casualties, 1/2-3/4 were directly caused by those geotechnical earthquake disasters. In addition, the remarkable amplification effect of thick loess deposit and topography on ground motion played an important role in collapse or seriously damage of houses and serious geotechnical disasters.

Since the 1980s, many scholars have carried out many researches on the characteristics and mechanism of the earthquake disasters of loess, such as seismic effect of the loess site, subsidence of unsaturated loess, liquefaction of saturated loess and landslides of loess slopes, and have made quite a lot of progress in the related research fields. Some research achievements have been applied in the engineering codes to guide the construction in the loess areas. However, due to the unique engineering geological characteristics and the complexity of topographic and geomorphological conditions of loess deposit, the related research work is still lacking in systematic. In this paper, the recent progresses in loess earthquake engineering including amplification effect of loess sites on ground motion, mechanisms and prevention of landslides, subsidence and liquefaction of loess are introduced. The application of the research achievements in the national and provincial engineering codes was discussed. The past cooperation between China and Europe in loess earthquake engineering are summarized. The fields of potential China-EU cooperation in the future are proposed.

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2. AMPLIFICATION EFFECT OF LOESS SITES

In the Loess Plateau, the investigation of earthquakes disasters, observatory data and tests shown that the thickness of loess deposit and the topography of loess site have very significant effects on ground motion. Usually earthquake intensity, PGA and it characteristic period of response spectrum of ground motion increased remarkably with increasing of loess thickness and height of slopes.

2.1 The effect of loess thickness on the amplification effect

In the aspect of the influence of the thickness of loess deposit on the amplifying effect of ground motion, Shi et al. (1999) summarized a large number of actual cases and studied the influence law of the thickness and topography of loess deposit on the amplifying effect of ground motion. The results show that with the increase of loess thickness, the peak acceleration of ground motion increases, and the period of the response spectrum moves to the long period. For different topographic conditions such as slope, loess Yuan and loess Liang, the amplifying effect would become more obvious on the ground motions with the increase of its height. Wan et al (2016) investigated the effect of loess thickness on response spectrum of ground acceleration based on a borehole profile of loess deposit by means of one-dimensional equivalent linearization method. The results showed that the peak value of acceleration response spectrum and characteristic period increased obviously with the increase of loess thickness and seismic intensity. Wu et al. (2009, 2011) studied the amplification effect of thick loess sites on HVSR peak value and its predominant frequency in Gansu province by means of microtremor observation. Wang et al. (2010) studied amplification effect of loess deposit and height of loess slopes on intensity degree, PGA and predominant period of ground motion during the Wechuan 8.0 earthquake in 2008 based on field investigation, ground motion observation and microtremor measurements, and found that earthquake intensity, PGA and characteristic period could increase with 1 degree and twice respectively by the amplification effect. Zeng et al. (2012) used the method 1/4 wavelength and loess thickness and predominant frequency statistics to invert the thickness of overburden in the loess area of Tianshui City, and verified that there is a good correspondence between the spectral characteristics of HVSR and the predominant frequency of the site.

In summary, previous studies have shown that with the increase of loess thickness, peak acceleration and characteristic period increase obviously. However, the related research results are still qualitative and the systematic quantitative amplification laws of loess thickness and topography on peak acceleration and characteristic period of ground motion has rarely been reported yet.

2.2 The Effect of site conditions on amplification effect

In the aspect of the research on the amplification effect of topography of loess deposit on ground motion, Wang et al. (2010) analyzed the impact of different elevation topography on the peak acceleration of ground motion based on earth tremor observation. The result shown that the topographical height difference of loess deposit is the key factor causing more serious damage on the top of a mountain. The peak acceleration on the top of the mountain could exceeds 2 times of that at the foot of the mountain. Chen et al (2012) investigated the strong aftershock acceleration records of different elevations in the same mountain by using the strong ground motion observation array in Gansu province, where was strongly affected by the Wenchuan 8.0 earthquake. Dynamic response analysis for loess sites with different overburden thicknesses and different slope under seismic loadings was carried out using the two-dimensional equivalent linear time-history analysis method. The results shown that the peak acceleration recorded on the top of the mountain is greater than that at the mountainside, while the peak acceleration at the mountainside is slightly larger than that at the mountain foot. The amplification effect of the peak acceleration is directly related to the loess thickness and the height of the loess slope. Liu (2010, 2012) studied the influence of topography conditions on ground motions by numerical analysis, revealed the reason why earthquake damage is aggravated by the amplification effect, and concluded that the amplification effect of the top edge of a mountain and the thickness of loess deposit on ground motion was significant, which was in good agreement with the statistical analysis. Wu et al. (2012) carried out seismic response analysis of loess

Yuan in Gansu and Shanxi province affected by the Wechuan 8.0 earthquake using two-dimensional equivalent linear time-history analysis method. It is found that the acceleration value at the top front of loess Yuan increases by 2 times than that at the bottom of highland, which is coincident with the conclusion of Yan et al. (2011). Sheng et al. (2013) analyzed the influence of different terraces of river valley on the peak acceleration of ground motion through numerical model. The results shown that the peak acceleration at the high terraces of the valley is larger than that at the valley bottom. In addition, the duration of ground acceleration increases with increasing of the slope angle of the valley. Wang (2011) studied the amplification effect of the valley and basin on the ground motion using the transfer function of ground acceleration time history recorded during the Wenchuan 8.0 earthquake, and concluded that the amplifying effect of soil layers site on the ground motion increased the high-frequency and low-frequency components. Ma et al. (2016) conducted seismic response analysis by inputting different seismic waves to the established loess site model, and found that the amplitude of ground motion spectrum increased in loess-covered valleys compared with bedrock valleys.

2.3 The application of loess site effects in the specification

The significant site effect in loess site has been considered in Specification for Seismic Design of Building in Gansu province "(DB62/T25-3055-2011)". In the provincial code, the construction site categories in the loess area should be determined based on shear wave velocity and thickness of the site soil layer. In mountainous area, the large and medium-sized construction sites with a large thickness of loess deposit should increase the measurement points of wave velocity. For the construction sites in strip-shaped solitary landform and the edge of the slope, the slope conditions such as the lithology, height and angle of the slope as well as the distance between the slope and the building should be investigated to consider the amplification effect of the topography on the ground motion parameters. For the loess sites thick than 50 m without topography influence (loess Yuan, big river valley, the sites far away from the edge of loess Yuan and slope), the seismic influence coefficient should be adjusted by times a factor of 1.1,1.2 and 1.3 respectively for the cases of 50m$\leqslant \Delta H <$100m, 100m$\leqslant \Delta H <$200m。

3. SEISMIC LOESS LANDSLIDES

In the loess plateau of China, the topography of loess deposit gradually reduced to elongated mountains or millions of gullies. Many strong earthquakes in history have caused numerous loess landslides, most of which were characterized by low angle and long-distance slip. According to statistics, the landslide distribution area of Tianshui Ms8.0 earthquake in 1654 was about 1000km^2, of which there were 59 landslides with a slip distance of more than 500m. The landslide distribution area of Tongwei Ms7.5 earthquake in 1718 is about 3500km^2, of which there are 337 landslides with a slip distance of more than 500m. The landslide distribution area of Ningxia Haiyuan Ms8.5 earthquake in 1920 was about 5000km^2, of which there were 657 landslides with a slip distance of more than 500m. In 1927, the Gulang Ms8.0 earthquake in Gansu caused more than 90 landslides. In 2008, the Wenchuan Ms8.0 earthquake caused secondary geological disasters in the Loess Plateau region more than 300km far away from the epicenter, especially the slope instability disaster was serious. In 2013, at the epicenter of the Minxian-Zhangxian Ms6.6 earthquake, forming a dense area of loess landslides with 30km long and 8 km wide. Among them, the slip distance of loess landslide on the west side of the Yongguang village was about 1km, burring 8 houses and made 12 people dead. A large number of landslides caused by earthquakes, burying towns and villages, damaging buildings and facilities, killing more than 1 million people, and resulting in countless property losses.

3.1 Research progress on behaviors and mechanics of earthquake induced loess landslide

Since 1970s, the researches on loess landslides induced by earthquakes have been carried out, mainly in landslide investigation, landslide classification, landslide characteristics, failure and slip mechanism, slip distance prediction and stability evaluation. Some of the research results have been adopted in the specifications to protect the safety of the building projects in the Loess area.

Liu et al. (1984) Carried out aerial photo interpretation of the large area loess landslide caused by the 1718 Tongwei Ms7.5 earthquake and the 1654 Tianshui Ms8.0 earthquake. Large scale seismic loess landslides field investigations of 1920 Ms8.5 Haiyuan earthquake have carried out by Zhang (1991), the mechanism of earthquake induced landslides in loess areas was divided into seismic subsidence unstability, liquefaction unstability and shear deformation unstability under the joint effect of seismic force and gravity. And the types of loess landslides were divided into collapse landslide, liquefaction landslide and seismic force (acceleration) induced landslide. Bai et al. (1990) analyzed the characteristics and mechanism of liquefaction-triggered low angle slip of a loess Yuan during the Haiyuan 8.5 earthquake based on field investigations and laboratory tests. Chen et al. (2006) made a statistical study of 147 typical seismic loess landslide, divided the types of seismic landslides into loess landslides, loess bedrock bedding landslides and loess bedrock mixed landslides. The classification based on failure mode can provide the basis for the study and prevention of landslide failure. Wang et al. (1999) had suggested that the saturation of loess may cause the shear strength decrease and the slip surface develop, the excess pore water pressure may cause further destruction of soil structure and increasing of residual deformation and pore water pressure. Saturated loess tends to liquefaction and high fluidity. When the loess deposit slides under the effect of earthquake, and the excess pore water pressure furtherly increased, which makes the liquefaction degree of loess mass increased, and the viscous force of the sliding body weakens further. Xie et al. (2001) believed that the loess in natural conditions is difficult to reach a full saturation, and there is still gas in the enclosed pores. The liquefaction and gasification effect of loess under seismic loading may cause high-speed and long-distance landslides. Wang et al. (2013), Xu et al. (2013) and Zhang et al. (2014) studied the characteristics and mechanism of loess landslide caused by the Minxian-Zhangxian Ms6.6 earthquake.

3.2 Research progress on hazards evaluation of earthquake induced loess landslide

Liu (2005) discussed the influence of dynamic pore water pressure on the stability of saturated loess infinite slope during earthquake and after earthquake. The dynamic stability analysis model of saturated loess infinite slope was established, and the failure of this kind of slope was divided into two basic types: liquefaction failure and sliding failure. Wang Jiading calculated the displacement of long-distance landslide according to the parabolic motion of the sliding body. Lu et al. (2006) divided the maximum slip distance into the displacement produced by the oscillation of the rock slope during the earthquake and the slip distance of the landslide after the stop of seismic shaking. The Newmark finite displacement analysis model was used to calculate the permanent seismic displacement of the former, and then the displacement of the latter was calculated. Using fuzzy information theory, Wang (2013) studied the characteristics and influencing factors of loess landslide in valley areas, and proposed a new method to predict the influence range of landslide by using mathematical analysis based on the fuzzy data. Sun et al. (2011) developed a judgment matrix of landslides under the coupling effect of earthquake and rainfall based on the probability theory, which involves comprehensive information of a slope, soil type, ground motion intensity and underground water level. Wang et al. (2016, 2017) presented a method of evaluating the sliding distance of the seismic landslides on the Loess Plateau, developed a formula for calculating the safety factor of loess slopes under the coupling effect of earthquake and rainfall and furtherly proposed a performance-based design method of loess slopes under the coupling effect.

3.3 Application of the research achievements on seismic loess landslides in seismic specification

The influence ranges of loess landslide have been adopted in Specification for Seismic Design of Buildings in Gansu province (DB62/T25-3055-2011). In the specification, normal buildings must set back a distance at least 5 times of relevant height of the slope from the top edge of the slope, and 1.5-2.5 times from the foot of the slope. In addition, the zoning map of loess landslides for cities with exceedance probability of 10% and 2% in 50 years was also presented for landslides disasters prevention.

4. LOESS LIQUEFACTION

Liquefaction of saturated loess is one of the three major seismic loess disasters, which is in parallel with loess seismic landslide and loess seismic subsidence. The Haiyuan 8.5 earthquake in 1920, the Tajikistan Ms5.5 Earthquake in 1989, the Wenchuan Ms8.0 Earthquake and the Minxian-Zhangxian Ms6.6 earthquake in 2013 induced soil flow or mud flow triggered by loess liquefaction, which caused tremendous casualties and property loss. Compared with the research on liquefaction of saturated sand and silt, the study on loess liquefaction was carried out relatively late. The related research mainly focuses on the mechanism, properties, evaluation and anti-liquefaction treatment of foundation, etc. The preliminary judgement method and evaluating method based on SPT test results have been adopted in the relevant specifications to guide the engineering design and construction in loess areas.

4.1 Research progresses on liquefaction properties of saturated loess

Due to its special mirco-structure and water-sensitive properties and the dissolution of soluble salts in the loess under saturated state, the strength of loess sharply decreased. Furthermore, because of the distribution of macro-pores supported by particles and a small part of the closed micro-pores, the pore water pressure increases along with the partially dissipation of pore pressure under dynamic loading. Therefore, its liquefaction properties are significantly different from saturated sand and saturated silt. Wang et al. (2000), Wang et al. (2011), Sun et al. (2008) conducted the liquefaction tests of saturated loess under cyclic loading by dynamic triaxial apparatus. It indicated that the dynamic strain of saturated loess has mutational characteristics when it reaches about 3%, and when the dynamic residual strain exceeds 3%, the dynamic strain will increase dramatically due to the structural destruction of saturated loess. Research of Wang et al. (2012) indicated that the characteristics of dynamic strain of saturated loess under cyclic loading are closely related to its micro-structure. Under the same amplitude of dynamic loading, the dynamic strain of saturated loess with weak cemented structure increases sharply due to the loss of structural strength, while the dynamic strain of saturated loess with bonding structure increases slowly. Based on the discussion of the influencing factors of pore pressure evolution of saturated loess under cyclic loading, Liu et al. (1994) proposed a development model of pore water pressure of saturated loess. Wang et al. (2000) considered that the pore water pressure development model for liquefaction of saturated loess under equal consolidation conditions can be described by a mathematical model composed of higher order polynomial. Liu et al. (2002) considered that the pore water pressure growth model of saturated compacted loess under equal consolidation conditions conforms to the A-type curve. She et al. (2002) proposed a A-type pore pressure growth equation in which the collapsible correction term is added considering the volumetric-change characteristic of loess under humidifying effect. Hu et al. (2009) concluded that the excess pore water pressure of saturated loess under cyclic loading is composed of elastic pore pressure and plastic pore pressure considering the structural properties of loess. The plastic pore pressure is caused by the plastic strain of soil, which directly affects the effective stress of soil. The increasing law of plastic pore water pressure ratio with residual strain was developed.

4.2 Research progresses of liquefaction properties of saturated loess

The factors that affect the liquefaction of saturated loess were studied involving in basic physical parameters, seismic loading characteristics and initial stress conditions. The research made by Wang (2000) indicated that more than 80% saturation of loess has a significant liquefaction potential. The silt content is closely related to seismic intensity required to trigger liquefaction, which decreases linearly with the increase of the silt content. Hu et al. (2009), Wang et al. (2011) found that the structural cementation degree of loess directly affects the development of pore water pressure and therefore plays a key role in the liquefaction of saturated loess. Structural damage is corresponding to an important turning point of dynamic performance of saturated loess. The research made by Boulanger et al. (1998) indicated that the plasticity index has a certain influence on the liquefaction resistance of saturated loess. The greater the plasticity index, the greater the liquefaction resistance. Wang et al. (2012), Deng et al. (2012) revealed that dynamic loading types have a significant impact on the liquefaction characteristics of saturated loess. Comparing with sinusoidal loading, the pore pressure ratio of saturated loess liquefaction under irregular seismic loading is larger, and the hysteresis of pore pressure response on the irregular loading is more obvious. Hu et al. (2009), Deng et al. (2012) found that dynamic loading amplitude increases lead to the decrease of liquefaction resistance for the same saturated loess. Pore pressure ratio increased linearly with dynamic loading amplitude. When it increases to a certain value, the residual strain of saturated loess increases rapidly until it damage. Hu et al. (2009) and Yang et al. (2004) found that the dynamic loading frequency has a little effect on the process form of pore water pressure ratio of saturated loess. However, as the frequency increases, the cyclic times of liquefaction increases and liquefaction resistance decreases. Wang et al. (2000) found that the increase of confining pressure will reduce cyclic times of liquefaction failure of saturated loess to a certain extent, but it has a little effect on the pattern of pore pressure evolution curve. Wang et al. (2011) found that with the increase of overlying soil pressure, liquefaction resistance of saturated loess will increase.

4.3 Liquefaction potential evaluation of saturated loess ground and anti-liquefaction technology

Judgement and evaluation of liquefaction potential of saturated loess ground are mainly based on laboratory tests and field in-situ tests. Wang et al. (2003) proposed a method of calculating the critical ground horizontal peak acceleration to induce liquefaction of saturated loess based on dynamic triaxial tests under irregular seismic loading. And then the liquefaction potential of loess site under certain seismic intensity may be evaluated by comparing the critical PGA with the designed PGA. In addition, the maximum value of shear wave velocity of loess with liquefaction potential at IX degree intensity is about 500m/s. Wang et al. (2012) proposed that the maximum shear wave velocity of loess with liquefaction potential at the equivalent seismic intensity of Ⅶ degree, VIII degree and IV degree is about 303 m/s, 385 m/s and 463m/s respectively. Wang et al. (2013) compared the results of standard penetration tests of 50 saturated loess sites in Gansu province with the judging results by Seed-Idriss simple method and give the reference value of the SPT blow count with the liquefaction potential of loess. When the designed peak ground acceleration is 0.1g, 0.15g, 0.2g, 0.3g and 0.4g, the corresponding reference value of SPT blow count are 7, 8, 9, 11 and 13 respectively.

In the aspect of anti-liquefaction treatment of loess ground, the research shows that the use of presoaking method, compaction pile method and replacement cushion method can only reduce the liquefaction potential of saturated loess ground to a certain extent, from He et al.(2001). Dynamic consolidation increases liquefaction resistance by increasing soil density of the ground, from Wang et al. (2013). Because loess liquefaction is closely related to particles size gradation and cementation of micro-structure, dynamic compaction cannot completely eliminate the loess liquefaction potential. The loess ground treated by dynamic compaction does not have the liquefaction potential when the equivalent seismic intensity is below Ⅶ degree. If the dry density after the treatment is more than 1.641 g/cm^3, or 1.767 g/cm^3 respectively, the liquefaction potential under the effect of seismic intensity below Ⅷ degree or IX degree may be eliminated respectively. However, the liquefaction potential of saturated loess ground can be completely eliminated by the chemical grouting method.

4.4 Application of loess liquefaction research achievements in seismic specification

The Specification for Seismic Design of Buildings in Lanzhou urban area (DB62/T25-3037-2006) requires the peak ground horizontal acceleration triggering liquefaction may be calculated based on the dynamic triaxial test results of saturated loess under irregular seismic loading. Then the loess liquefaction potential under a certain seismic intensity may be evaluated by comparing with the PGA by which the site would be affected in the future. The Specification for Seismic Design of Buildings in Gansu province" (DB62/T25-3055-2011) " proposes a method for evaluating liquefaction potential of loess sites and anti-liquefaction treatment of saturated loess ground. The method includes two stages, preliminary judgement and detailed judgement. The preliminary judgement is carried out based geological age, clay content, and saturation of loess ground as well as non-liquefied soil thickness overlaying shallow natural foundation and groundwater level. For the detailed judgement, the reference value of SPT blow count with liquefaction potential of saturated loess is provided. The liquefaction grade of loess ground is classified according to liquefaction index. Moreover, a method of calculating the negative skin friction and the horizontal thrust of pile foundations is presented. The treatment measures against the liquefaction potential with slight, moderate and serious liquefaction of loess grounds are proposed. The seismic design method of pile foundation in liquefiable loess ground and the treatment technology against liquefaction of loess ground are given. In addition, the zoning maps of liquefaction potential of Lanzhou City, Tianshui city and Qingyang city in 50 years with exceedance probability of 10% and 2% was also provided.

5. SEISMIC SUBSIDENCE

Strong earthquakes in the history induced seismic subsidence of loess sites. Such as, The Huaxian 8.0 earthquake in Shannxi province in 1556 caused a seismic subsidence of more than 1 meters of the drum-tower's loess ground in Weinan County, which also developed a great deal of fissures in loess deposit. In 1718, The Tongwei 7.5 earthquake in Gansu Province caused "flat subsidence" in loess sites except many landslides. In 1920, the Haiyuan Ms8.5 earthquake caused inhomogeneous seismic subsidence in a flat thick loess deposit (Loess Yuan) except a large number of landslides，which induced serious fissures in loess deposit in Baicaoyuan. In 1995, the Yongdeng 5.8 earthquake resulted in step-like subsidence along the top of mountain at Gedagou. The research in seismic subsidence of loess began in the early 1980s. Since then, the progresses in the mechanism, evaluation and treatment of seismic subsidence of loess sites have been generally gained with the improvement of various test techniques, such as dynamic triaxial test instrument, dynamic torsional triaxial test apparatus, electronic scanning microscope and field blasting technology.

5.1 Research progress in the mechanism of seismic subsidence

The unique microstructure of loess determines its engineering geological properties. In a preliminary study, Zhang et al. (1999), Wang et al. (2003) explained the phenomenon of loess seismic subsidence by the damage and collapse of porous microstructure of loess under dynamic loadings. The main factors of influencing seismic subsidence of loess including water content, void ratio, dry density, consolation stress, cyclic times and dynamic loadings were studied. A empirical formula of evaluating dynamic residual strain was established. In 2007, DENG Jin analyzed the interaction between particles and pores based on the principle of gas-solid surface of loess, and established the calculation formula of seismic subsidence coefficient of loess, the quantitative study of microstructure used in seismic subsidence of loess started.

5.2 Research progress in seismic subsidence estimation

Seismic subsidence is a variable influenced by many factors. Gu et al. (2007), Su et al. (2007), Li et al. (1985), Xu et al. (2006) analyzed the relationship between dynamic residual strain and the influencing factors of soil physical parameters, stress condition and loading condition, and proposed the maximum depth of loess deposit which may develop obvious seismic subsidence.

Seismic settlement quantity is the basis for evaluating seismic subsidence of loess site, which may be used for classifying the disaster grade of seismic subsidence and determining appropriate ground treatment technology. The key to calculate the seismic settlement quantity is to obtain the seismic subsidence coefficient of each loess layer. Wang et al. (1993) presented a layered summation method based on the empirical formula of estimating seismic subsidence coefficient. Deng et al. (2005) established a semi-empirical and semi-theoretical formula for estimating loess seismic subsidence coefficient using microstructural characteristics parameters. Chen et al. (2008) established an formula of estimating seismic subsidence coefficient according to the statistical relationship between physical parameters of loess and seismic subsidence. Wang et al. (2017) constructed a simplified calculation model of seismic site subsidence combining with the increment formula of seismic subsidence coefficient and the correspondence between earthquake magnitude and equivalent cyclic times.

5.3 Research progress in seismic subsidence treatment

The settlement of building's ground is the direct disaster consequence of loess seismic subsidence. Since the mechanism of loess seismic subsidence is similar to that of collapsibility due to the destruction of porous microstructure and compaction consolidation. Therefore, the collapsible loess treatment method is used as reference for studying treatment technology of loess seismic subsidence. Wang et al. (2003) proposed the treatment techniques of dynamic compaction, compaction piles and chemical grouting to reduce and eliminate seismic subsidence of loess. Wang et al. (2016) used the fly ash to improve the loess site against seismic subsidence, and studied the change of seismic subsidence characteristics under dynamic loadings. The results have shown that the collapsible loess treatment technology such as dynamic compaction, compaction pile and chemical grouting is usually effective in mitigating and eliminating loess seismic subsidence. Comparatively speaking, there are few research on underground engineering safety problems related to loess seismic subsidence, it is only found in the interaction between pile and soil, from Sun et al (2010) and Zhao et al.(2007). The study on seismic safety of underground engineering in loess seismic subsidence obviously lags behind other types of soil, and does not fit in with the need of engineering construction. Therefore, it is necessary to further study the influence and treatment of seismic subsidence on the tunnel, subway and underground pipeline in loess sites.

5.4 Application of loess seismic subsidence in seismic specification

The method of evaluation and treatment of loess seismic subsidence is provided in The Specification for Seismic Design of Buildings in Gansu province" (DB62/T25-3055-2011). For Class A and B buildings with seismic fortification intensity≥8 degree and Class C buildings with seismic fortification intensity≥8 degree (0.30g), It can be judged as seismic subsidence loess ground when the void ratio (e) ≥0.95 or relative density(η) ≤0.7 and the water content (ω) ≥20%, or saturation degree (Sr)≥0.65; or shear wave velocity (Vs) ≤150m/s. The seismic subsidence hazards could be divided into slight, moderate and serious grades according to the thickness of seismic subsidence loess, 5m, 5-10m, >10m. As the reference, the loess seismic subsidence zoning maps of Lanzhou City, Qingyang city and Tianshui city with exceedance probability of 2% and 10% for 50 years are attached respectively. The sites with slight, moderate and serious seismic subsidence are respectively classified into general site, adverse site and dangerous site.

6. CHINA-EUROPE COOPERATIONS

In the past 30 years, China and Europe have carried out a lot of cooperative researches in the fields of loess dynamics and loess seismic engineering. From 1991 to 1994, Dr. Tom Dijkstra of the British Geological Survey visited Lanzhou University for three times for a very comprehensive and deep study in Sale Mountain landslide, Heifangtai landslide, landslides in Lanzhou Basin and the method of landslide risk assessment.

Since 2008, Lanzhou Institute of seismology, CEA has invited Professor Kyriazis Pitilakis of the University of Aristotle in Greece, academician Victor I. OSIPOV and Professor Nadira G.Mavlyanova of the Russian Academy of science, Dr. Tom Dijkstra of the British Geological Survey to visit Lanzhou China for academic exchange and cooperative research in site effect, landslides, seismic subsidence and liquefaction of loess deposit and providing consultation for the reconstructions of the Wenchuan 8.0 earthquake and the Minxian-Zhangxian 6.6 earthquake in the field of the mechanism of landslides under coupling effects of earthquake and rainfall, shaking table test technique, geological disasters identification and risk assessment and zoning technology.

Lanzhou Institute of seismology, CEA and Lanzhou University sent researchers to first-class universities in Europe for further studies and the scientific research was fruitful. For example, Under the supervising of Prof. Kyriazis Pitilakis, Dr. Binghui Song studied small-strain stiffness and damping of Lanzhou loess by means of torsional resonant column tests in University of Aristotle in Greece. Based on the tested results, the influences of water content, confining pressure, consolidation time and soil structure on stiffness (G_0) and damping (D_{min}) at small strain of Lanzhou loess were investigated. The relevant relationships were established with empirical formula. The research results may provide a valuable reference for seismic response analysis of loess sites.

In the future, China and Europe will also carry out further research cooperation in the field of geodynamics and seismic engineering, we suggest that the main directions of cooperation include but not limited to: Physical and dynamic characteristics of Loess; the risk assessment method of loess landslides under the coupling of earthquake and rainfall; mode and mechanism of earthquake geological disasters chain in Loess Plateau; long-term effect and risk assessment method, zoning technology of seismic geological hazards; emergency disposal technology of seismic geological hazards; dynamic damage mechanism and catastrophic characteristics of the loess site under the complex stress condition, and the seismic treatment technology for loess ground. We sincerely hope that both sides can seize the opportunity of Chinese "The Belt and Road" initiative, promote the China- Greece cooperative project to be put into practice in Seismic hazard, risk assessment and mitigation technologies for urban sites, sites of important cultural heritage and critical transportation infrastructures subjected to seismically induced landslides.

7. CONCLUTION

The Loess Plateau is strong earthquake-prone region with catastrophic seismic geological disasters, where landslides and debris flow are also induced frequently. In history, earthquakes caused 1.4 million people dead in the plateau. At present, there are more than 50 large and middle cities, many large scale infrastructures and important engineering projects, and about 150 million population in this area. Therefore, both seismic risk and geological hazards risk are very high in the plateau.
The many progresses in the mechanism, evaluation and prevention of seismic landslides, liquefaction, seismic subsidence and site effect of loess deposit have been gained. China and Europe, where loess is distributed, has established a good relationship of academic exchange and cooperation in loess dynamics and loess earthquake engineering.
It will provide a sufficient seismic safeguard for “The Belt and Road” to carry out China- Europe cooperative research in Seismic hazard, risk assessment and mitigation technologies for urban sites, sites of important cultural heritage and critical transportation infrastructures subjected to seismically induced landslides.

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