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**Research Article**

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# Study on tunnel safety incipient danger and countermeasures optimization in high-terrace folk house in Kashgar city

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**ABSTRACT**

*The high-terrace folk house in Kashgar has a widely distribution of tunnels and underground storage space under the building, which bring a great incipient danger to the stability of the building and the slope. Two typical incipient dangerous working condition of tunnel stability are studied with the Realistic Failure Process Analysis (RFPA) code, considering collapsible loess mechanical property of heterogeneous distribution characteristics. In RFPA code, elastic damage mechanics is a method used for describing the constitutive law of the meso-level element, and the maximum tensile strain criterion and the Mohr–Coulomb criterion are utilized as the damage threshold. In the numerical modeling with RFPA, the acoustic emission (AE) event rate is employed as the criterion to intuitively describe the dynamic evolution of soil mesoscopic damage - fracture extension - fracture plane formation -local or overall instability for tunnels and underground storage space failure. The maximum risk and critical condition of the two kinds of working condition are obtained. In view of the complexity and difficulty of the tunnels backfill work in Kashgar, two feasible suggestions are put forward.*

**Key words:** High-terrace folk house; tunnel; safety incipient danger; RFPA; stability analysis

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## INTRODUCTION

Kashgar city is located in the earthquake zone where most of ancient architecture has been out of repair for long years and old towns have poor seismic capability. Most of the old houses are dangerous ones, including all the houses with thatched roof and mud wall. Thinking from the traumatic experience of "Bam earthquake" in 2003 and "Wenchuan Earthquake" in 2008, government at all levels and local Uyghur residents are eagerly aware that substituting the new-type earthquake-resistant buildings for the dilapidated houses in the old city is an immediate priority [1].

In February 2009, the State officially initiated the *Comprehensive Treatment Project of Reconstruction of Dangerous and Dilapidated Buildings in Old Town of Kashgar City*. And in August 2010, Comprehensive Treatment Project of Reconstruction of Dangerous and Dilapidated Buildings in Old Town of Kashgar was approved for implementation. The aim of the project was that it would take five years to reconstruct the dangerous and dilapidated houses, tear down all dangerous buildings to rebuild novel Uyghur earthquake-resistant houses since 2010. In addition, total investment of the project was more than 7 billion RMB and protective restoration was implemented according to the requirements of National Famous Historical and Cultural City.

There are plenty of artificial cave under Kashgar high-terrace folk house and local residents use it for storing fruits. In addition, since the State called for “digging holes deeply, accumulating grain widely”, plenty of air-raid shelter was constructed under the old Kashgar city during the Cultural Revolution. These caved tunnels would cause displacement and deformation of the surface, which would result in harmful effect, such as differential settlement and cracking. The tunnels and caves once led to collapse of houses. When it rained or snowed, tunnel would collapse frequently, giving rise to serious threats to lives and property of residents. Recently, tunnel collapse accident happened on January 26, 2010. Due to the drainage pipeline jam, sewage flowing into tunnel caused tunnel collapse whose length was approximately 8 meters, depth was approximately 2 meters and width was approximately 4 meters, which severely threatened the surrounding 4 residents' lives and property safety.

For the research about tunnel collapse, there have been a lot of important achievements that mainly concentrate in two aspects [2-5], that is, one is analysis of tunnel stability, failure mechanism, strengthening treatment and monitoring; the other is the building damage, tilting, cracking, distortion and reinforcement measures. The above achievements are acquired by adopting continuum mechanics, so it is difficult to comprehensively demonstrate evolution of local rupture. However, the loess characteristics of Kashgar high-terrace folk house have the properties of sudden and non-uniform subsidence. In this article, on the basis of inhomogeneity of soil and combining the actual local geological conditions and the tunnel distribution characteristics, the software Realistic Failure Process Analysis (RFPA) [6-8] has been adopted to simulate and analyze the potential danger of the tunnel and to evaluate and optimize the practical process.

## NUMERICAL EXPERIMENTAL SECTION

***Geological conditions of engineering***

Kashgar area displays narrow band shape and extends northwest, and underground layers consist of Paleozoic sector, Devonian sector, Carboniferous-Permian, Tertiary and Quaternary. There is a high level of undulating, with the north area higher than the south area, and the whole layers display ladder-like distribution patterns.

According to Kashgar Quaternary geological conditions and accumulated data during geological survey, the features of geological conditions of high residential buildings are obvious and could be divided into three layers. The upper layers are loose soil, consisting of filling clay, powder clay, clay and other loose clay types. The intermediate layers mainly consist of loess-like loam, and the lower layers mainly consist of silt. The cohesion of miscellaneous clay c is 9.3kPa, the internal friction angle is 5 °, and the clay density is 1800Kg/m3; the cohesion of loess c is 45.93kPa, the internal friction angle is 13.67 °, and the loess density is 2000Kg/m3; the cohesion of silt c is 269.5kPa, the internal friction angle is 18.4 °, and the silt density is 2300Kg/m3.

***Establishment of numerical model***

Based on the consideration of widely distributed tunnels and underground storage space beneath high-terrace folk house, two typical risk conditions are proposed as follows: one is that tunnel is proximally orthogonal to underground storage space; and the other is that both are proximally paralleled to each other. The actual dimension of high-terrace folk house used in numerical model is 1 meter high and the length is 5 meters, whereas the dimension of underground storage space is 1.5 meters. In addition, each loading unit is 0.08MPa, that is, uniformly distributed load is generated by tall building above the tunnel.

The model is only affected by self-weight in the vertical operation and building load and it can move vertically if left and right boundary conditions are used to limit sliding bearing of horizontal displacement; if the bottom boundary condition serves as restricted sliding bearing of vertical displacement, two corners of the bottom and the side restrict horizontal and vertical displacement, serving as fixed support.

The first numerical model of risk condition is illustrated in Fig.1 in which the distance between tunnel and underground storage space is 3 meters. Horizontal scale in the model is 30 meters, while vertical scale is 15 meters, which is totally divided into 300×150=45000 units.

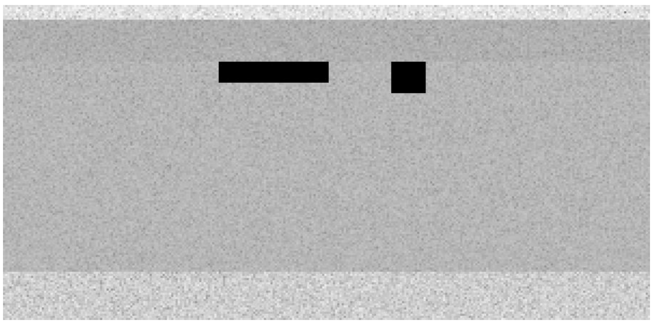


**Fig. 1 Simulation test model of tunnel orthogonally near to underground storage space**

The second numerical model of risk condition is illustrated in Fig.2 where the distance between tunnel and underground storage space is 4.5 meters. Horizontal scale in the model is 28 meters, while vertical scale is 15 meters, which is totally divided into 280×150=42000 units.

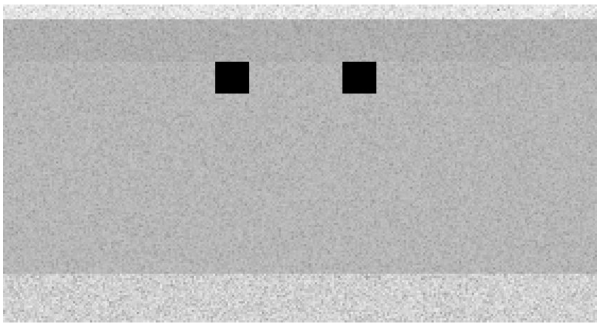


**Fig.2 Simulation test model of two closely parallel underground storage space**

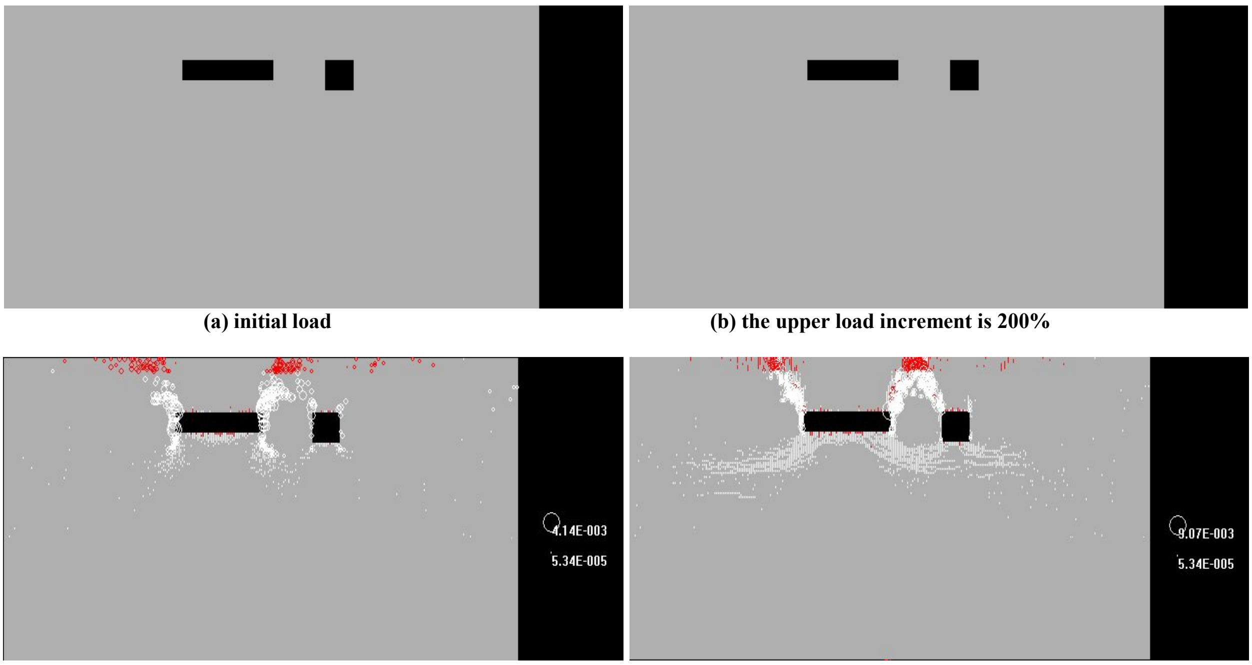
## RESULTS AND DISCUSSION

Acoustic emission signal can signify strain energy released due to internal micro crack propagation. Observation and analysis of acoustic emission behavior of the geotechnical materials can help us to deduce the change of the internal structure of rock and soil mass and to understand the location, the time and the strength of the micro crack.

RFPA system can simulate the process of crack initiation, extension and penetration in the geotechnical materials, at the same time, it can also obtain spatial and temporal distribution in the above process of acoustic emission and the strength released by the elastic energy. In the RFPA system, the number of destroy unit is used to indicate acoustic emission number, and the damage strain energy release unit denotes energy release of acoustic emission. Different types of damage are denoted with different colors of circles in which a white circle denotes shear failure happened in unit and the red circle denotes tensile failure happened in unit.

***The first kind of risk condition instability process***

Fig.3 shows acoustic emission distribution of distortion and breakage on the condition that tunnels and underground storage space are proximally orthogonal just beneath high-terrace folk house, which intuitively reflects dynamic evolutionary rules of the internal rock and soil model: mesoscopic damage - fracture extension - fracture plane formation -local or overall instability.




**(a) initial load** **(b) the upper load increment is 200%**

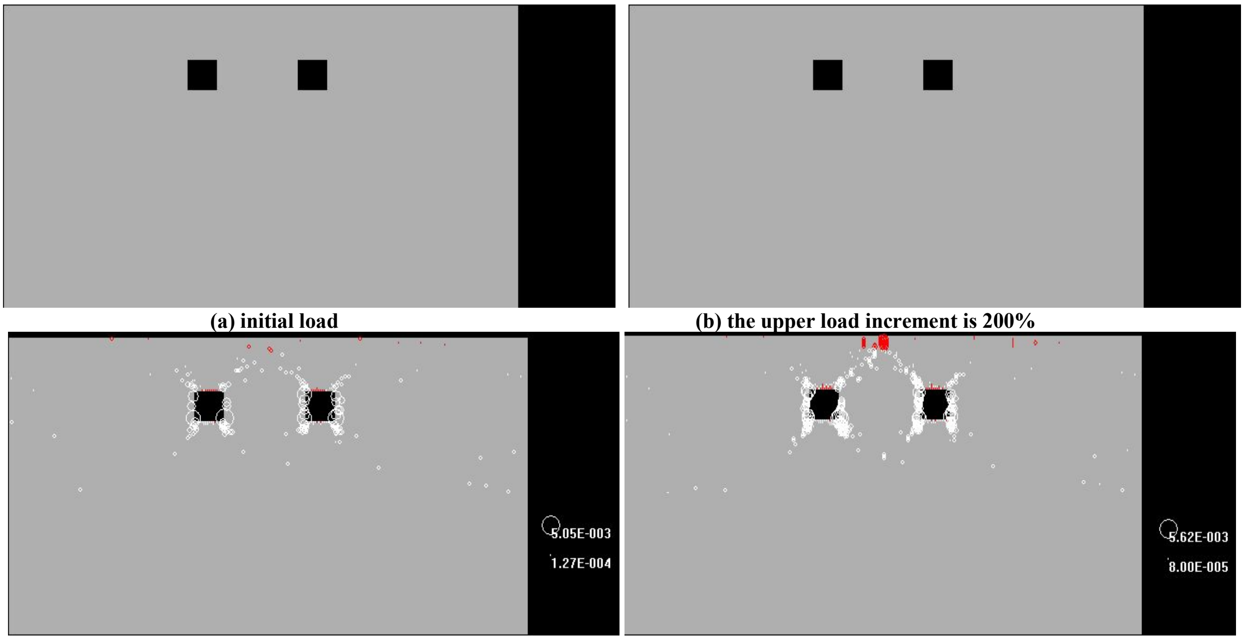
**(c) step 1 when upper load incremental is 300%** **(d) step 12 when the upper load increment is 300%**

**Fig.3 The changing AE failure process of tunnel orthogonally near to underground storage space**

As shown in the fig 3, with the increase of top load (corresponding to increase of the height of the house), when the load intensity increases to 100% and 200% of the initial intensity, it is said that the house is increased to 2-storeyed height and 3-storeyed height, and we can see no mesoscopic damage occurs inside the local loess, and no break in weak connection, which won't cause crack. When the load intensity increases to 300% of the initial intensity, that is to say, the house is increased to 4-storeyed height, then the house begins to appear damage in the region of low intensity due to the nonuniformity of loess. Firstly, mesoscopic damage appears on the top of tunnel, and then the cracks extend upward. As can be seen from the acoustic emission color, it is red, and the corresponding to red is tensile damage; On the border of tunnels and underground storage space appears a lot of mesoscopic damage, resulting in cracks, local dip and collapse, and as can be seen from the acoustic emission color, it is red, and the corresponding is tensile damage; In the junction between tunnels and underground storage space, because of stress, large numbers of microscopic damage appear, and seen from its color, it is white, and what corresponds to it is compression and shear failure, which will cause instability of building foundation damage followed by appearance of fracture on the wall. As a whole, with the increase of the damage, the stability is worse and worse, and large area of roof collapses, meanwhile the above buildings collapse and tilt, which affects buildings around 5m.

***The second kind of risk condition instability process***

Fig.4 shows acoustic emission distribution of distortion and breakage on the condition that two underground storage spaces are proximally paralleled just beneath high-terrace folk house, which intuitively reflects dynamic evolutionary rules of the internal rock and soil model: mesoscopic damage - fracture extension - fracture plane formation -local or overall instability.




**(a) initial load** **(b) the upper load increment is 200%**

**(c) step 1 when the upper load incremental is 300%** **(d) step 10 when the upper load increment is 300%**

**Fig.4 The changing AE failure process of two closely parallel underground storage spaces**

The figure shows that the destruction process is consistent with the first instability process, and in terms of two proximal-paralleled underground storage spaces, with the increase of upper load (corresponding to increasing process of houses), when the load intensity increase to 100% and 200% of the initial intensity, namely the house increases to the 2-storeyed and 3-storeyed, it can be seen that there is no mesoscopic damage in the internal loess and no rupture in weak connection, causing no building crack. When the load intensity increases to 300% of the initial intensity, that is, the house increases to 4-storeyed height, due to the inhomogeneity of loess, the unit of low intensity starts to damage. Firstly, the top of two underground storage spaces start to crack, As can be seen from the acoustic emission color, it is red, and the corresponding to red is tensile damage; The above building foundation shows mesoscopic damage, causing local crack, and it is red in terms of acoustic emission color, so the corresponding to red is mainly tensile damage; On the border of two underground storage spaces, due to the stress a lot of mesoscopic damage appears, and as can be seen from the color, it is white, the corresponding is the compression and shear failure, which will cause instability of building foundation damage followed by appearance of fracture on the wall. As a whole, with the increase of the damage, the tunnel stability is worse and worse, at the same time, the buildings right above the junction between two underground storage spaces are the most dangerous, which affects buildings around 6m, but the degree of impact is smaller than the first potential dangerous working condition.

Fig.3 and Fig.4 show that in terms of two kinds of typical risk condition, there will be a massive destruction process induced by geotechnical local damage when buildings are increased to more than 4-storeyed. The border of tunnels and underground storage space and the junction between two underground storage spaces are the most dangerous areas, showing the most serious damage. The corner around underground space is also possibly dangerous area whose damage is invisible, which actually reflects the dangerous conditions, such as cracking and tilting.

***Tunnel treatment and countermeasures optimization***

In the old city reconstruction, methods applied to tunnel include gypsum grouting method and concrete filling method. To test the effect of these two methods in the tunnel reinforcement, we compared similarities and differences between the construction progress and method procedures, at the same time we compared advantages and disadvantages of two methods in different environment, geological conditions. Besides that, we analyzed construction cost and comprehensively inspected the quantity and the quality of engineering. Supervising Unit randomly sampled in the completed tunnel, shafted to the top of tunnel fillings to conduct flooding experiments, measured the permeability coefficient of reinforced soil and evaluated the compactness of reinforced soil and reinforcement effect. After the inspection, two kinds of construction technique can satisfy the requirements of specification, and it is suggested that, in the future, when dealing with the tunnel engineering of core zone in the old city, it should be reasonable to choose different construction technique according to the construction safety environment, terrain conditions and geological conditions.

Although both methods of gypsum grouting and concrete filling have great advantages, for collapsible loess in high-terrace folk house, the two methods exist the biggest problem that the differences between gypsum or concrete and collapsible loess mechanics characteristics (such as intensity, elastic modulus, Poisson's ratio and stiffness) are too big. Under the long-term effects of the upper load, uneven characteristic of stress diffusion in the lower part of the building foundation have formed. When the stress is transferred to gypsum or concrete, interfaces between collapsible loess and gypsum or concrete begin to produce damage, and then the accumulated damage causes mesoscopic fracture developed to failure plane. Once the failure plane is formed, local or entire instability would occur. Then Protective renovation work will cause unpredictable and incalculable loss in the future. Fig.5 shows the damage distribution after filling tunnels with gypsum and concrete. The underground storage space on the left is backfilled with gypsum grouting method, while the underground storage space on the right is filled with concrete filling method, furthermore, the size of the model and material characteristics are the same as the second numerical model. Compared with concrete material, Poisson's ratio and intensity of gypsum material is much smaller, and the tensile strength of concrete is greater than that of gypsum and soil. As shown in Figure.5, there is crack area caused by tension in the underground storage space filled with gypsum material, while there is no damage in the underground storage space with concrete material. However, there is a large amount of shear failure between the underground storage spaces, whereas both sides of the soil are in a state of shear compression, visually showing the process and the characteristics of damage due to the differences of material strength and deformation characteristics.

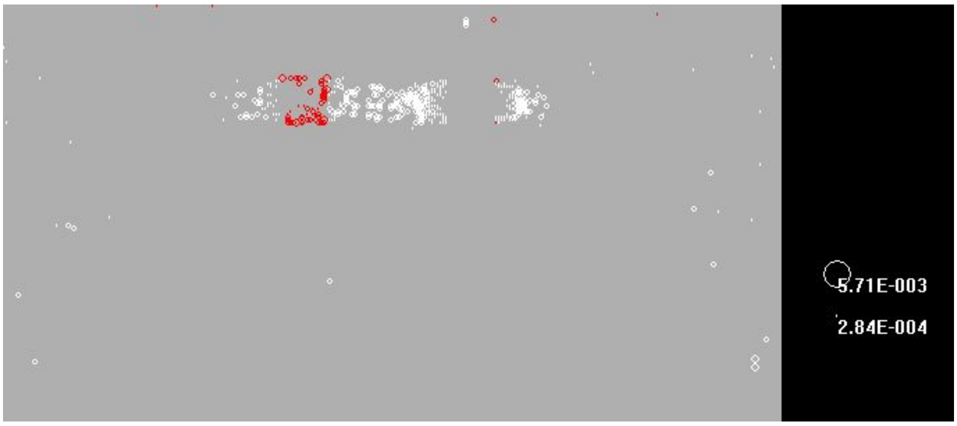



**Fig.5 The changing AE failure process of two underground storage space filled with gypsum and concrete**

Based on the results of numerical model, in the article, there are two suggestions on tunnel backfill for high-terrace folk house: the first suggestion is, for high-terrace folk house, that we should make them understand the importance and urgency of backfill work which is mainly operated by family and supported by government's subsidies; The second suggestion is that backfill material should be operated in the form of the original soil backfill bags so as to avoid damage and destruction due to material strength and deformation in the future.

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