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A proposed solution to the ground fissure encountered in urban metro construction in Xi'an, China

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ABSTRACT

The city of Xi'an, Shaanxi, China, was founded over 3000 years ago. However, the city faces urban geological hazards with 14 parallel ground fissures covering a wide area of the municipal area. The ground fissures are not only hazardous to surface buildings, structures and underground pipes but also pose a major safety risk to the 15 metro lines under construction or under planning. Such challenges are unprecedented in the history of metro construction around the world. Research indicates that the ground fissures in Xi'an produce three-dimensional motion, among which the vertical displacement has the strongest effects on metro engineering. The results of large-scale physical model tests suggest that damages such as cracks in tunnel lining, failures of waterproofing and deformation of metro rail can be caused by the activities of ground fissures. To mitigate such risks, this paper proposes a series of engineering countermeasures such as enlargement of tunnel sections to maintain clearance, use of segmented tunnels, enhancement of tunnel lining, and use of multiple waterproofing measures. These countermeasures have been proven to be effective and reliable, based on the successful operation of the Xi'an Metro for the past 3 years.

1. Introduction

The upsurge of human engineering activities, excessive pumping of underground water, and other tectonization activities such as earthquakes lead to the surge of the geological hazards of ground fissures in many regions across the world, including America, China, Mexico, Australia, and Kenya, Ethiopia in Africa, etc. (Holzer, 1984; Bell et al., 1992; Lee et al., 1996; Li et al., 2000; Rojas et al., 2002; Ayalew et al., 2004). Ground fissures in China are widely distributed, such as those in Suzhou, Wuxi and Changzhou, North China plain, Xi'an, etc. Among these, the ground fissures in Xi'an city are the most typical ones that cause severe damages. Xi'an, one of the oldest and most important capital cities in Chinese history, is located in the middle of the Guanzhong Basin, Shaanxi Province, China. It is the birthplace of the Chinese nation and is known as one of the 'Four Civilized Ancient Capitals' together with Athens, Rome, and Cairo. However, the excessive exploitation of underground water since the 1950s has resulted in the formation of at least 14 ground fissures in Xian (Fig. 1). These represent a serious geological hazard, due to their potentials to cause cracks and damage buildings, deform roads and bridges, rupture underground openings and pipelines, cause deformation and inclination of historical sites such as the ancient City Wall. These ground fissures are still active and pose serious restrictions on urban planning and construction. Although many studies have been carried out on active ground fissures, most have focused on the geological characteristics such as the spatial distribution, formation mechanisms and activity characteristics. There has been very limited research on the influence of active ground fissure on engineering structure such as metro tunnel, including the damage mechanisms and defensive measures (Holzer, 1984; Zhang, 1990; Sandoval and Bartlett, 1991; Carpenter, 1993; El Baruni, 1994; Lee et al., 1996; Sheng and Helm, 1998; Shlemon and Simon, 1998; Li et al., 2000; Ayalew et al., 2004; Peng, 2012; Peng et al., 2013).

Xi'an City features a permanent population of over 8 million, the dense population make it essential for the metro system to be a key component of a multi-level urban transportation system.

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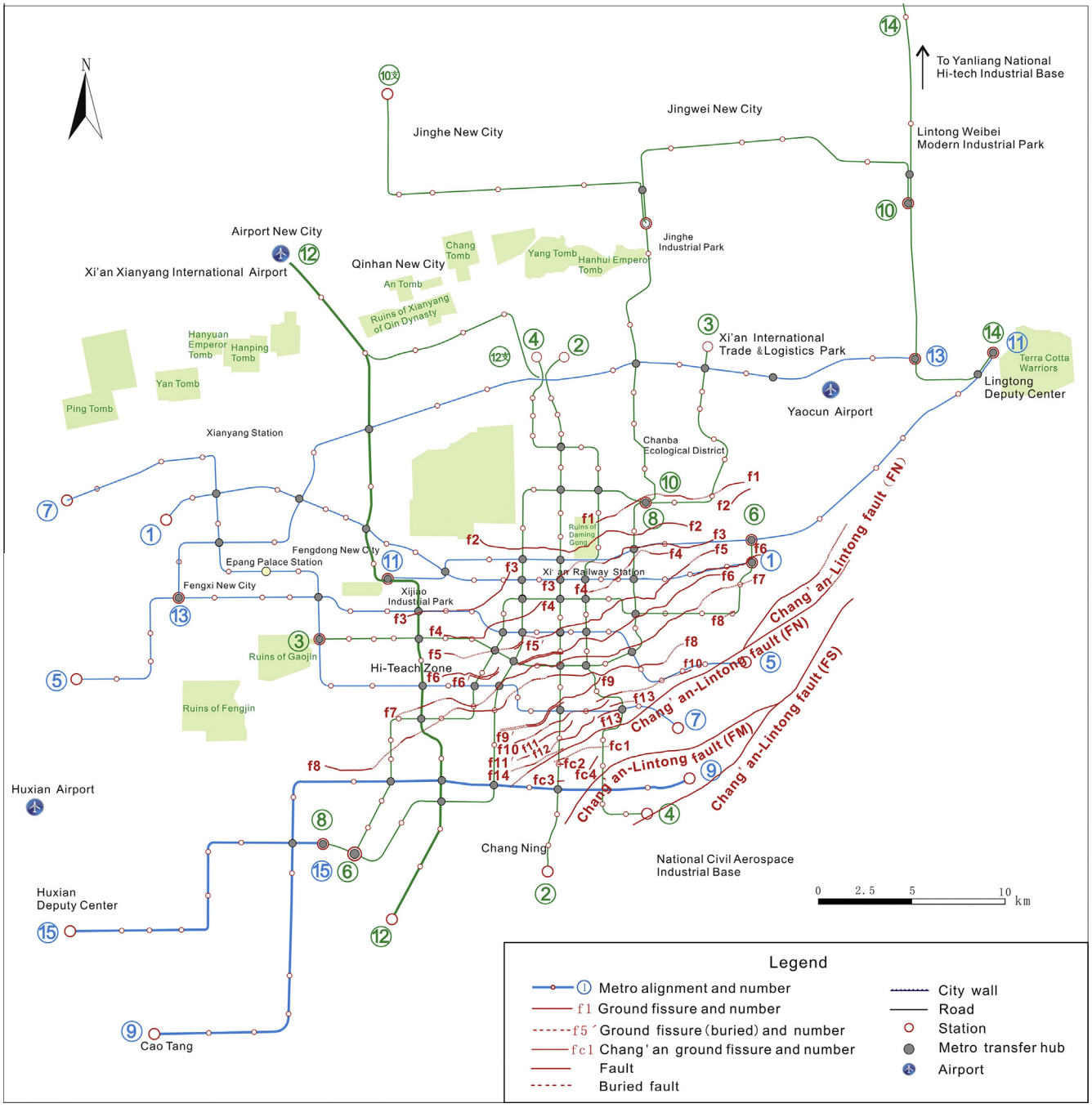

Fig. 1. Distribution of ground fissures and the metro lines network in Xi'an, China.

However, the Xi'an Metro was initially designed using linear engineering, making it vulnerable to the effects of ground fissures (Fig. 1). The 15 planned metro lines (some of which have been constructed and are in operation) intersect with the 14 ground fissures at about 100 locations. It is imperative to institute effective countermeasures to safeguard the metro tunnel against damages by ground fissures. This study was conducted to assess the engineering risks posed by ground fissure activities, and to determine effective countermeasure for damage prevention and/or control and to guarantee safe operation of the Xi'an Metro.

Ground fissures represent a scientific and engineering challenge to both geologists and civil engineers. In this paper, solutions are proposed to mitigate these hazards, based on a systematic design of model experiments considering the geological features and engineering hazards associated with the ground fissures in Xi'an.

2. Geological characteristics of ground fissures

2.1. Spatial distribution

Xi'an is located at the hanging wall of the southern Chang'an-Lintong active fault zone, which possess a series of secondary hidden faults with a strike of NEE in the strata. The ground fissures in Xi'an have developed because of the excessive pumping of underground water, which has activated the underlying faults and caused instability to the surface layer (Fig. 2; Peng, 2012). Surface geological investigation indicates that the spatial distribution of the 14 ground fissures in Xi'an (The ground fissures are serially numbered f_1 to f_{14} from north to south) exhibits many characteristic features, such as directional extension, banding distribution and approximate uniform spacing, with the distance between each pair