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Experimental modeling of segmental shallow tunnels in alluvial affected by normal faults

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ABSTRACT

Faulting is one type of permanent ground displacement and tunnels are at the risk of damage from faulting because of their long lengths. There are few studies that examine the behavior of tunnels intersecting the fault zones although it is of continuing concern for design engineers. Determining the failure mechanism provides critical information for the design of a tunnel, including its segmental lining. The present study conducted a series of centrifuge model tests on segmental tunnels subjected to normal faulting. The results indicated the absence of sudden failure of segmental tunnels under normal faulting and improvement of function in response to an increase in the overburden of the tunnel. The angle of the fault affected tunnel behavior. Despite large displacement faulting, structural damage to the segments was very low because of the adequate geometric functioning of the segments and their joints. The length of the zone affected by faulting in the tunnel decreased as the overburden increased, but the severity of damage increased in response to localization of fault displacement. Sinkhole formation upon the collapse of soil into the tunnel is likely at the ground surface. Special attention must be paid to the effect of sinkholes on at ground structures in the vicinity of the tunnel.

1. Introduction

The use of urban tunnels is increasing to accommodate lifelines such as roads, railroads, subways, sewer systems and high voltage electrical cables. Many cities sit on sedimentary deposits and faulting zones, which presents challenges for the construction of these tunnels. The building codes of many countries recommend avoiding construction in the vicinity of active faults, but at times construction of a tunnel intersecting a fault is inevitable (Loukidis et al., 2009; Anastasopoulos and Gazetas, 2007a).

It is not always possible to avoid construction of a tunnel near an active fault (Lee and Hamada, 2005). This can affect the design of the tunnel lining. Such a tunnel must be capable of resisting fault displacement so that it will suffer only minor damage. Highly active faults can cause significant damage to a tunnel. Fault displacement can produce extreme stress on the lining of the tunnel. The study of tunnel behavior passing through a fault zone during an earthquake is practically unknown.

The current study investigated the effects of normal faulting on shallow segmental tunnels using physical modeling in a geotechnical centrifuge. This article describes the details of physical modeling of a normal fault, a segmental tunnel in a centrifuge, and the results of nine centrifuge tests. The result of this paper can be used for determination of failure modes, loading conditions and lining characteristics that are important factors in tunnel design.

1.1. Faulting hazards

One type of probable damage is that caused by permanent ground displacement (PGD). Severe earthquakes can cause such displacements to appear at the ground surface and cause fractures called surface faulting. The interaction of surface faulting with at ground structures such as bridges, dams, and buildings or underground structures such as tunnels and pipelines can result in major damage to them. Comprehensive studies have been conducted to fully understand this phenomenon (Bray et al., 1994; Pamuk et al., 2005; Konagai, 2005; Lin et al., 2006; Anastasopoulos et al., 2007, 2008; Gazetas et al., 2008; Ng et al., 2012; Oettle and Bray, 2013; Anastasopoulos and Gazetas, 2007a,b; Bransby et al., 2008a,b; Fadaee et al., 2013; Rojhani et al., 2012). These studies clearly indicate that in areas at risk of faulting, it is essential to employ designs to minimize damage caused by PGD. Past research on the effects of faulting on structures has focused more

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on aboveground structures. Despite the importance of underground structures such as tunnels, they have been less-frequently investigated.

Iran is one of the most seismically-active regions and has high potential for the occurrence of surface faults. Major Iranian cities such as Tehran, Tabriz and Mashhad are located in seismically-active areas with many known and unknown faults. For example, a well-known fault in northern Tabriz runs through to northwest, north and northeast of the city. Urban development around Tabriz means that this fault passes through the newly-established suburbs to the north of the city. Fig. 1 one shows the fold caused by a fault in route of line 2 of the Tabriz metro.

Not all faults in a location are known, although they may become active and are identified during an earthquake. It is not uncommon for unknown faults to be detected during geotechnical excavations. It is known that several parts of Tabriz are located on faulted ground. The need for more effective public transportation systems in cities such as Tabriz make tunneling a necessity, which increases the risk of faulting that threatens underground structures such as subways and transportation tunnels (Kiani et al., 2013). It is possible for a subway tunnel to intersect a fault. This has occurred in many large cities and there are many urban tunnels built in fault zones. Fig. 1 shows Tabriz metro line 2, which intersects the fault zone to the east of the city.

1.2. Damage to tunnels

Records show that tunnels in some areas are vulnerable to earthquake damage. Table 1 lists past damage to tunnels around the globe. Existing resources do not report the type and level of damage to segmental tunnels, probably because it is a more recent tunneling method.

1.3. Previous research

Literature review shows that limited research has been done on the effect of faulting on tunnels. A selection of previous research on this subject is presented in Table 2 of these, only Burridge et al. (1989) and Baziar et al. (2014) have modeled their studies in a centrifuge; the remaining studies used either 1 g modeling or field studies. None modeled segmental tunnel lining. Examination of the studies listed in Table 2 indicate, that little research has been carried out to investigate the effect of faulting on tunnels. In addition, segmental linings and tunnels have not previously been modeled in a centrifuge. Also, less attention in physical modeling has been paid to failure modes and mechanisms; most studies have focused on the behavior of a tunnel near a fault before total failure. This study presents greater insight into damage mechanisms to further development of design criteria when considering fault rupture loading.

2. Experimental method and apparatus

The main purpose of the modeling was to understand and recognize the mechanisms of probable failure. Understanding these mechanisms and the effective parameters, such as tunnel overburden and the angle of the fault, are essential to the proper design of segmental lining. The diameter of the model tunnel closely approximated the common diameter of twin subway tunnels. Fig. 2 is a flowchart of the progression of this research.

2.1. Geotechnical centrifuge

The Actidyn centrifuge at Tehran University is the first geotechnical centrifuge of this size in Iran and was used for the present

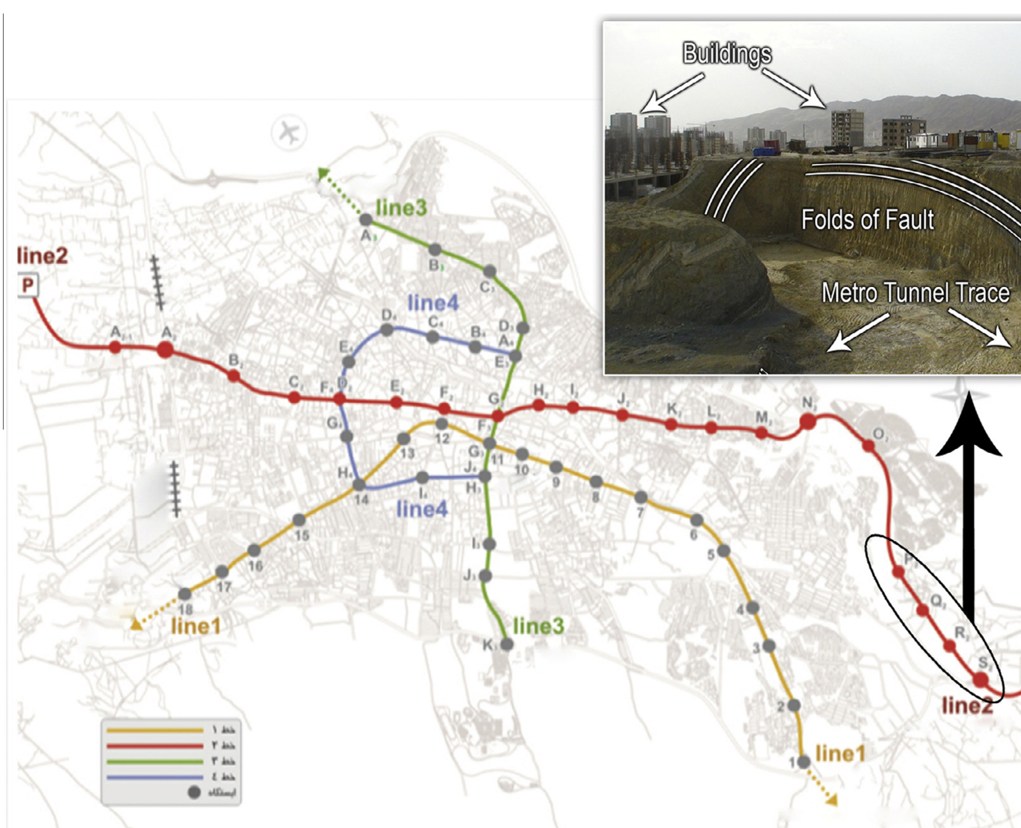

Fig. 1. Line 2 of Tabriz metro and probable faulting zone.