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Performance evaluation of tunnels built in rigid soils

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ABSTRACT

Shallow tunnels less than one kilometer long located in stiff soils, such as cemented silty sands or sandy silts, are prone to be constructed by Conventional Tunneling, CT, as defined by the International Tunnel Association, ITA. In particular, special caution has to be exercised when conducting fully open face excavation, in cemented fine-grained materials due to the potential of fragile failure that these soils may exhibit, which can lead to catastrophic unforeseen damage to surrounding structures. Localized ground movement, associated to low safety factors at the face, unsupported tunnel crown, and walls may preclude progressive failure that could even propagate to the surface terrain depending on the thickness of the upper crust of soil on top of the tunnel. This paper presents a two-step novel approach proposed to conduct the performance evaluation of tunnels built using CT, which is aimed at unifying the revision of both state limits of failure and service. Initially, the relation between strength and deformation parameters is established through statistical analyses of the soil properties, and then, the Bivariable Point Estimate Method, BPEM, coupled with tridimensional finite difference models is used to compute factors of safety, probabilities of failure, reliability indexes, and tunnel settlements at critical areas of the soil mass surrounding the tunnel. The method is introduced through a case study corresponding to a critical section of one of the five tunnels found in a strategic 15 km long urban highway that was recently built in the north east area of Mexico City. Tridimensional finite difference models were developed with the program $FLAC^{3D}$. Two variants of the construction procedure were evaluated, shotcrete only, and shotcrete with steel frames as primary lining. From the numerical studies, insight was gained regarding the expected tunnel behavior as a function of the support system.

1. Introduction

Modern tunnel design and construction in heavily populated urban areas requires a proper definition of State Limits of Failure, SLF, and Deformation, SLD, to ensure both the best solution from the economic stand point, and also to avoid costly failures during construction. In particular, special caution should be exercised when dealing with conventional tunneling, as defined by the International Tunnel Association, ITA Working Group (2009), considering that it is more sensitive to inherent uncertainties associated with both spatial and temporal soil properties variability, than other tunneling methods, such as the Earth Pressure Balance, EPB, technique. This is quite notorious when dealing with stiff cemented sandy silts and silty sands, such as those found in the north east portion of Mexico City, due to potential strain softening that may preclude local failures and led to global progressive failures. Several famous failures, when using these construction techniques with traditional design methods, have been extensively documented in the technical literature (Melis, 2007; Masín, 2009; Connor and Diederichs, 2013). Two approaches have been followed by practitioners to overcome this limitation: (1) use over conservative factors of safety to guarantee a proper tunnel performance (Fortsakis et al., 2013), or (2) conduct a thoroughly tunnel risk management study (ITA Working Group, 2009; Degn et al., 2004; Guglielmetti et al., 2008). This paper presents a two-step novel approach aimed at unifying the revision of state limits of failure and service through Performance Based Design, PBD. In practice, this method can be used to quantify tunnel risk, within a risk analysis framework (Degn et al., 2004; Guglielmetti et al., 2008; Low and Einstein, 2013; Zhao et al., 2014). Initially, a multilinear regression analysis is carried out to derive a relationship among the deformation parameters of the soil mass (in the case analyzed herein Young modulus, E) and the strength parameters (cohesion, c, and friction, ϕ). Then, the Bivariable Point Estimate Method, BPEM (Harr, 1996; Rosenblueth, 1975a,b, 1981) is used to establish the factor of safety distribution, probability of failure and reliability indices at the critical zones around the tunnel. The parameter E

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was taken for this study as the secant modulus of the stress–strain curve passing through the 50% of the peak strength, E_{50}. Factors of safety at critical areas around the tunnel, and ground movements for the four combinations of c and ϕ, obtained following the BPEM, and the corresponding deformation parameter E_{50}, estimated from the statistically-derived relationship $E_{50}(c, \phi)$, were computed with tridimensional finite different models developed with the program FLAC^{3D} (Itasca, 2009). From these results, probabilities of failure and reliability indexes were obtained for the actual soil conditions found at the critical tunnel section. This analysis framework is applied to assess the performance of a tunnel built recently in fine-grained cemented materials in Mexico City surroundings, with CT. This tunnel is part of a major highway, and is identified as Tunnel 4. The tunnel response during construction is studied as a function of factor of safety for the tunnel face, upper tunnel portion referred herein after as crown, and tunnel walls, establishing for each case the probability of failure, reliability index, and expected ground deformations during construction, considering two lining configurations: (1) reinforced shotcrete, and (2) reinforced shotcrete and steel frames. The analyses focus only on the geotechnical aspects. Therefore, it is considered that the liner is designed to withstand the actual loads with a proper safety factor, this is most of the cases established based on capacity diagrams of the lining system (Connor and Diederichs, 2013; Fortsakis et al., 2013). A major advantage of this methodology is that both SLF and SLD are revised simultaneously, allowing to account for the construction procedure explicitly in the performance evaluation assessment during the numerical modeling. Furthermore, this approach also addresses the effect of strength variability due to several degrees of cementation and fines content, which is a key issue in overall tunnel performance assessment in tobaceous soils. From the analyses, the relative efficiency of each liner configuration was established. Settlements distributions at several depths were also computed for the actual soil conditions.

2. Project description

Supervia project is comprised of five tunnels of length varying from 26 m, the shortest one, to 960 m the longest one. Fig. 1, shows the location of the project, and in particular of Tunnel 4, with respect to the geotechnical Mexico City zoning (RCDF, 2004). As can be observed this highway runs through the so called hill zone. From the geological stand point, this zone falls within the Tarango formation, which is comprised mostly by very cemented silty sands and sandy silts, dense to very dense, and exhibits large to very large shear strength and low compressibility. However, sometimes manmade clayey fills, or pockets of lose sand, can also be found. In particular, Tunnel 4, is 600 m long approximately, and it is found between chainages 13 + 330 and 13 + 930. This tunnel was built by two contractors using CT, with two different configurations of primary lining: (1) 30 cm thick shotcrete, and (2) 30 cm thick shotcrete with steel frames WI, 10 cm height, and an umbrella of autodrilled micropiles as required, in the tunnel entrance and exit. From chainages 13 + 330 to 13 + 630, it will be used alternative 1, whereas, from 13 + 630 to 13 + 930, it will be used alternative 2.

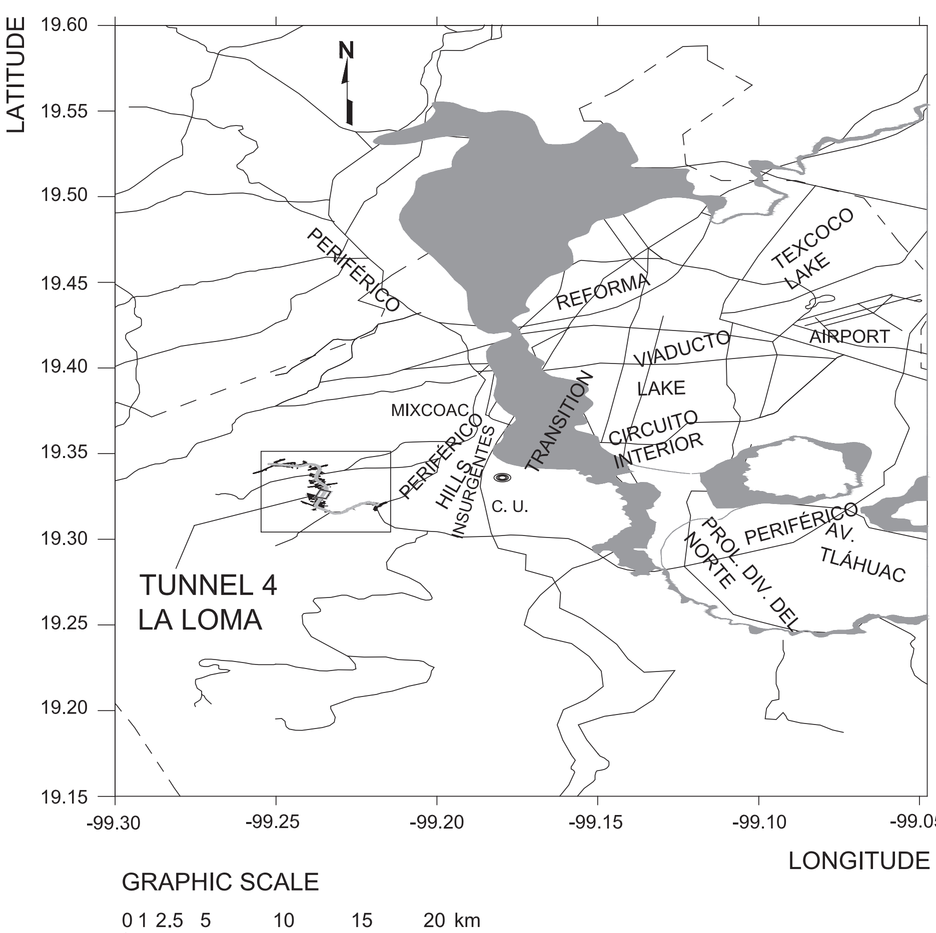

Fig. 1. Project location and geotechnical zoning.