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Investigation of gravity effect on penetration resistance in Tongji-1 lunar regolith simulant by centrifuge tests

Mingjing Jiang [a,b,c,*], Banglu Xi [b,c], Huayang Lei [a]

[a] School of Civil Engineering, Tianjin University, Tianjin 300072, China

[b] State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China

[c] Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji University, Shanghai 200092, China

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Abstract

Cone Penetration Tests (CPTs) are usually performed on the lunar regolith simulant on the Earth to study the geotechnical characteristics of lunar soil, which will be then used for the possible human activities on the Moon in the future. However, the gravity effect should be fully investigated before applying these experimental results to the Moon exploration, because the gravity level on the Moon is much lower than that on the Earth. For this aim, a series of CPTs was carried out in a centrifuge with a carefully designed testbed made of Tongji-1 lunar regolith simulant (TJ-1 simulant). The measured results were employed to examine the applicability of two traditional solutions and linear equation in describing the gravity effect along with some other existing experimental data. In addition, the linear equation fitted by the experimental data was used to predict the values of normalized tip resistances of lunar soil on the Moon. The results show that the two traditional solutions cannot describe the gravity effect well while the linear relationship between the peak (stable) normalized cone tip resistance and the reciprocal of gravity level can quantitatively describe the gravity effect on the penetration resistance. The predicted normalized peak (stable) tip resistances are larger than those of lunar soil on the Moon, which may be probably due to the unique in-situ conditions on the Moon.

Keywords: CPT; Centrifuge test; Gravity effect; Tongji-1 lunar regolith simulant

1. Introduction

Since the early exploration of the Moon in 1961, investigation of the geotechnical behaviors of lunar soil has attracted a lot of attention in different countries for the possible human activities on the Moon, e.g., In-Situ Resource Utilization and permanent outpost construction. Various physical model tests have been carried out on lunar soil simulant on the Earth in past decades, including the excavation test (King et al., 2011; Agui et al., 2013; Green et al., 2012; Iai and Gertsch, 2012), cone penetration test (CPT) (Houston and Namiq, 1971; Oravec, 2009; Jiang and Wang, 2013; Jiang et al., 2013c), plate loading test (Perkins and Madson, 1996; Bui et al., 2009; Kobayashi et al., 2009; Hao et al., 2015; Jiang et al., 2016), lunar rover test (Yoshida et al., 2003; Xiao and Zhang, 2016; Zhou et al., 2016; Jiang et al., 2017a). All the tests have already enhanced our knowledge of the geotechnical properties of the lunar soil on Earth. However, before applying this knowledge to Moon exploration, the gravity effect should be fully investigated to design the human activities safely and economically. Otherwise a series of engineering disasters may appear or much unnecessary cost may be needed. This is because the gravity level, which affects the

* Corresponding author at: School of Civil Engineering, Tianjin University, Tianjin 300072, China.

E-mail address: mingjing.jiang@tongji.edu.cn (M. Jiang).

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mechanical properties of soils significantly, is much lower (e.g. 1/6*g*) on the Moon than on the Earth. Actually, in the last two decades, a lot of attention has been paid on the gravity effect on the mechanical and geotechnical properties of lunar soil by performing various physical model tests, such as the excavation test (Boles et al., 1997; Boles and Connolly, 1996; Jiang et al., 2017b), plate loading test (Bui et al., 2009) and repose angle test (Nakashima et al., 2011).

This paper aims to investigate the gravity effect on CPT, which is an efficient in-situ test method widely used in geotechnical community to determine the geotechnical mechanical and engineering properties of soils and delineate soil stratigraphy on the Earth. The presented investigation was performed for the China Moon Exploration program. Since the CPT apparatus is easy to transport and use on the Moon, it has been already used in the Soviet Lunokhod rover missions (e.g., Cherkasov and Shvarev, 1973) and the U.S. Apollo missions (e.g., Costes and Mitchell, 1970; Campbell et al., 1973; Mitchell et al., 1972, 1973). Efforts have also been made to investigate the gravity effect on CPTs in previous studies. Costes et al. (1971) carried out CPTs on a parabolic flight with 1/6*g*, 1*g* and 2*g*. The measured results showed that both the average resistance and its average rate of change with depth increase with the gravity level, and can be used in combination with bearing capacity theory to determine the in-place shear strength characteristics of the soils testbed. Houston and Namiq (1971) suggested a solution to determine the penetration resistance of lunar soil by examining a lunar soil simulant on the Earth at first and then extending the test results to the lunar application. The results indicated that the reducing factor of the penetration resistance due to the lunar gravity is less than six, which is the factor relating the terrestrial and lunar gravity level. Instead, an average factor of about four is suggested. Since centrifuges can produce different gravities larger than 1*g*, many researchers performed the CPTs in a flying centrifuge to study the gravity effect or stress effect on tip resistance since the mid-1980s (Almeida et al., 2011; Bolton et al., 1993; Kim et al., 2013; Lee, 1990; Mo, 2014). Gui et al. (1998) analyzed the stress level effect by carrying out penetration tests in a centrifuge and the results demonstrated that the normalized tip resistance decreases with the increasing gravity level. Bałachowski (2007) analyzed the stress level and particle size effects on the tip resistance by performing penetration tests in a centrifuge. The results also showed that the normalized tip resistance decreases with the increase of stress level. Liu and Lehane (2012) analyzed the effect of particle shape on the tip resistance by performing a series of centrifuge tests at three different gravity levels, i.e., 50*g*, 100*g*, 200*g*. Although the gravity effect was not further analyzed in their study, significant gravity effect can be observed in their experimental results. Jiang et al. (2015) employed DEM to simulate the penetration tests on loose granular ground under widely different gravity levels from 1/6*g* to 20*g*. The results indicated that the maximum and stable normalized cone tip resistances can both be uniquely expressed by a linear equation (proposed by Jiang et al., 2015, which will be introduced in Section 4.2 and named the linear equation hereafter) in terms of the reciprocal of gravity. In contrast to the linear equation, there are several theoretical or empirical solutions proposed by geo-researchers (e.g., Durgunoglu and Mitchell, 1975; Houlsby and Hitchman, 1998) to predict the tip resistance in sand, which is stress-level-dependent and thus can be associated with gravity level in this paper (which will be given in Section 4.1). However, these equations were proposed based on either DEM simulations or experimental data on sand whose mechanical behavior is different from lunar soils to some extent. Thus, their applicability needs examined by experimental tests before being applied in practice for the China Moon Exploration Program, which constitutes a strong motivation for this study.

In this paper, a series of CPT centrifuge tests was carried out on Tongji-1 lunar regolith simulant (TJ-1 simulant) at different gravity levels to examine the applicability of two traditional solutions and the linear equation, along with some other existing experimental data. Following a brief introduction to the carefully designed testbed and apparatus accounting for the grain size and boundary effects, the penetration velocity effect was firstly investigated to select a proper penetration velocity. Then a series of CPTs was carried out at different gravity levels and the measured data were employed to validate two traditional solutions and the linear equation, together with some other experimental data available in the literatures. Finally, the linear equation whose parameters were determined by the experimental data was used to predict values of the peak (stable) normalized tip resistances of lunar soil in 1/6*g* field, which were then used to analyze the existing in-situ data on the Moon.

2. Experimental setup and methods

2.1. Centrifuge

The centrifuge employed in the paper is the TLJ-150 centrifuge at the Department of Geotechnical Engineering

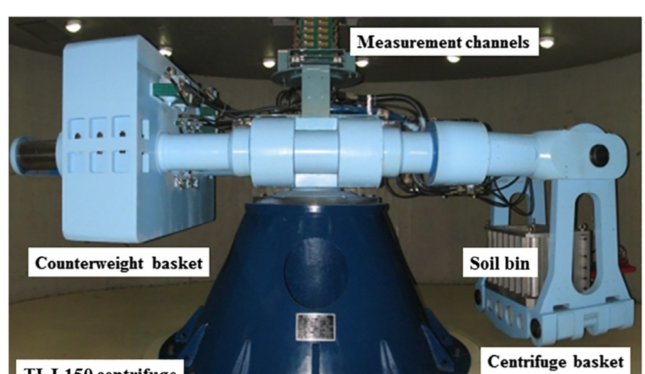

Fig. 1. TLJ-150 geotechnical centrifuge at Tongji University.

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