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Application of a new constitutive model to the analysis of plate load tests in a pyroclastic rock

Angelo Amorosi [a,1], Stefano Aversa [b,2], Daniela Boldini [c,*], Anita Laera [d,3], Marco Valerio Nicotera [e,4]

[a] Politecnico di Bari, Department of Civil, Environmental, Construction and Chemical Engineering, via Orabona 4, 70125 Bari, Italy
[b] Università di Napoli Parthenope, Department of Engineering, Centro Direzionale di Napoli, Isola C/4, 80143 Napoli, Italy
[c] Università di Bologna, Department of Civil, Chemical Environmental, and Materials Engineering, viale Terracini 28, 40131 Bologna, Italy
[d] Plaxis bv, Research, P.O. Box 57, 2600 AN Delft, The Netherlands
[e] Università di Napoli Federico II, Department of Civil and Environmental Engineering, via Claudio 21, 80125 Napoli, Italy

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ABSTRACT

This paper deals with a new critical state-based constitutive model for soft rocks and with its application to the analysis of the response of a pyroclastic rock during in situ plate load tests. The model, formulated in the single-surface plasticity framework, is characterised by the following main features: (i) a generalised three-invariant yield surface capable of reproducing a wide set of well-known criteria, (ii) the dependency of the elastic stiffness on the current stress state by means of a hyperelastic formulation and (iii) the ability of simulating the plastic strain driven structure degradation processes by a set of appropriate isotropic hardening laws. The constitutive model was implemented in a commercial Finite Element code by means of an explicit modified Euler scheme with automatic sub-stepping and error control. The procedure does not require any form of stress correction to prevent drift from the yield surface. The model was applied to simulate the response of a pyroclastic rock, the Neapolitan Yellow Tuff, to in-situ plate load tests conducted by 500 mm and 300 mm circular plates. In particular, in each location a first test was carried out adopting the large plate, applying a loading and unloading cycle; this was followed by a second loading stage performed on the same portion of rock by the smaller plate up to larger stress levels. Test results pointed out some specific features of the rock response under such loading conditions, including non-linear elastic behaviour and structure degradation, this latter highlighted by the overall reduction of the shear strength parameters. The numerical analyses showed a fairly good agreement with the in-situ experimental data, substantiating the relevance of the selected constitutive assumptions for the soft rock under investigation.

1. Introduction

The mechanical behaviour of soft rocks is characterised by features that fall in between those of soils and rocks.[1] In fact, irrespectively of their depositional environment (e.g.: sedimentary, volcanic), this class of materials shows non zero tensile strength and related cohesion together with pressure dependant elastic response and shear one, this latter leading to either fragile behaviour or – for larger confining pressures – a ductile one.[2] In the last decades a number of experimental observations have shown that the mechanics of soft rocks, like calcarenites and tuffs, is significantly affected by the so called structure effects.[3] Their initial stiffness and strength are considerably affected by the initial interparticle bonding, whose plastic strain-induced damage leads to significant modification of the overall behaviour of the material.[4] The above experimental evidences have triggered the interest towards the formulation of new constitutive models specifically devoted to soft rocks.[5–7] Among others, it is worth mentioning the significant contributions by Nova and co-workers[8–11], aimed at casting into the critical state soil mechanics framework the above soft rocks' mechanical features by means of hardening plasticity theory.

The specific soft rock studied in this paper is the Neapolitan Yellow Tuff (NYT). The city of Napoli (Italy) is located in the middle of a wide volcanic region formed by the Vesuvius and the

* Corresponding author. Fax: +39 051 2090247.
E-mail addresses: angelo.amorosi@poliba.it (A. Amorosi), stefano.aversa@uniparthenope.it (S. Aversa), daniela.boldini@unibo.it (D. Boldini), a.laera@plaxis.com (A. Laera), nicotera@unina.it (M. Valerio Nicotera).
[1] Fax: +39 080 5963675.
[2] Fax: +39 081 5476777.
[3] Fax: +31 15 2573 107.
[4] Fax: +39 081 5938936.

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Phlegrean Fields districts at the South-East and West of the town respectively. The subsoil of the urban area mainly consists of pyroclastic soils and rocks originated by the eruptions of the volcanic district of Campi Flegrei. Pyroclastic soils (*pozzolana*) generally overlay the lithic part of the Neapolitan Yellow Tuff and other pyroclastic tuffs. It follows that shallow and deep foundations, in the urban area of Napoli, are frequently seated on top of an underlying tuff layer. The design of such foundations is typically based on empirical approaches.

Pellegrino[12] investigated on the mechanical response of small diameter circular foundations on NYT by means of plate load tests performed on the formation during the construction of a tunnel excavated in the urban area of the city. In particular, loading and unloading tests were first carried out along seven different verticals by means of a circular plate of 500 mm of diameter, up to a maximum average vertical stress equal to 9 MPa. Those tests were then followed by a coaxial reloading performed at the same locations adopting a smaller plate ($d=300$ mm), up to a maximum average vertical stress of 25 MPa.

At that time no theoretical framework for describing the constitutive relationship of a soft rock (i.e. the tuff) and related advanced numerical tools for simulating plate load tests were available. In fact, the tests results were interpreted by means of the finite element (FE) method assuming a non linear elastic constitutive model.[12] The numerical analysis performed by the Author was not very satisfactory: for a single set of parameters he could only manage to simulate the average behaviour observed during the first series of plate load tests ($d=500$ mm), while failing to reproduce the subsequent series of coaxial plate load tests performed by the smaller plate ($d=300$ mm).

More recently other researchers[13] attempted to simulate the same set of data performing FE analyses adopting a Cam-Clay based model to account for some more recent findings on the mechanical behaviour of Neapolitan tuff.[14–16] The Authors adopted different sets of parameters for the same tuff, depending on the presumed degree of destructuration[3,4,15] induced by the loading. This simplified approach was meant to account for the mechanical effects of the first loading cycle on the subsequent plastic-strain-induced damaged behaviour observed during the smaller plate's tests.

In the following a new critical state-based hardening-plasticity model for soft rock is proposed. The formulation is aimed at reproducing some of the specific features of soft rock response, as the non-linear elastic behaviour, the pressure dependency of the shear response and the structure degradation, this latter implying a reduction in dimensions of the yield surface capable of modifying the yield stress under isotropic compression and a modification of the tensile and frictional components of the strength. The model relies on a flexible formulation of the yield surface, originally proposed by Bigoni and Piccolroaz[17], which allows to adapt its shape under both meridian and deviatoric sections to the available experimental data. The model is then tentatively applied to analyse, by means of the FE approach, the results of the in situ plate load tests performed by Pellegrino.[12]

2. Physical properties and mechanical behaviour of Neapolitan yellow tuff

Many pyroclastic rocks and soils outcrop in the Campania Region; their presence is primarily related to volcanic activity in the Phlegrean Fields and only in a few cases of Vesuvius. Among the rocks, the Neapolitan Yellow Tuff (NYT) is the most common in the first hundred metres below the ground level, covering approximately 300 km^2. The NYT forms the most important hills in the Phlegrean areas and in the city of Napoli. This material originated approximately 11–13 kyears b.p. during one or more volcanic eruptions in the Phlegrean Fields.[18–20]

NYT has been studied extensively at the University of Napoli Federico II: the first systematic experimental investigation on its mechanical behaviour dates back to more than forty years ago.[2,12] A number of significant contributions were added starting from the 80 s, once new experimental and theoretical tools were available to study this peculiar soft-rock.[14–16] Comprehensive reports on the NYT physical and mechanical properties were published by Evangelista and Aversa[16] and Evangelista and coworkers[18]

The structure of NYT is characterized by a fine matrix with pumiceous inclusion of small sizes. Lithic inclusions are frequent and their diameter is generally less than some millimetres. This soft rock has a porosity ranging from 0.4 up to 0.6 and a dry unit weight in the range from 10 kN/m^3 to 14 kN/m^3. The uniaxial compressive strength of NYT varies from about 1 MPa up to 10 MPa and is strongly related to the dry unit weight but it is also significantly affected by other structural features. Pellegrino[2], analysing the mechanical response of NYT and other tuffs as emerged from isotropic and triaxial compression tests, observed that they may show a rock-like or a soil-like behaviour as the mean effective stress varies from low to medium and high values. In the first case the tuff essentially behaves elastically up to plastic yielding or failure while in the second one it shows a ductile behaviour characterised by accumulation of plastic strain from the beginning of the test, similarly to a normally compressed and unbounded clayey soil. In particular, the Author concluded that for isotropically compressed triaxial tests the transition from the rock-like to the soil-like behaviour occurred when the mean effective stress achieved during the consolidation stage approximately doubled the uniaxial compressive strength. Finally, the Author sketched in the triaxial stress space the curve that bounded the rock-like domain; this curve actually identifies the stress states that produce the destructuration of the tuff, in accord with the general framework proposed by Leroueil and Vaughan[3] twenty years later.

Nova[8] carried out a first attempt to model the mechanical behaviour of the tuff by means of hardening plasticity theory. Subsequently, other researchers[15,21] pointed out the influence of destructuration phenomena on the mechanical behaviour of tuff. In particular, the experimental results obtained by Aversa and Evangelista[15] demonstrated that during an isotropic compression test positive hardening and degradation of the tuff developed at the same time. These two competing phenomena resulted in both an expansion of the yield surface and a contraction of its cross section in the meridian plane (i.e. a reduction of the critical state soil mechanics parameter M), leading to an overall reduction of the normalised shear strength of the material. It results that both size and shape of the yield surface of the tuff are modified by the strain history experienced by the material.

The mechanical behaviour of the specific NYT at the test site discussed in this paper was studied by means of laboratory tests by Pellegrino.[12] The material is characterised by a specific gravity $G_S=2.47$, a dry unit weight $\gamma_d=12.0$ kN/m^3 and a void ratio $e=1.20$.

Uniaxial compression tests were extensively carried out, leading to a mean value of about 4.4 MPa (Fig. 1).

A series of drained triaxial tests were also performed, isotropically consolidating the samples up to mean stress p ranging from 1.1 MPa to 10.2 MPa. This set of data proves to be reliable in terms of yield points identification, while providing less significant information for large strain shearing, as most of the specimen experienced significant strain localisation leading to shear banding. The yield points as deduced by a careful analysis of the triaxial data are shown in Fig. 2, together with a possible interpolating yield surface, described in details in Section 6 of this paper.