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Original article

Modelling the failure mechanisms of Michelangelo's David through small-scale centrifuge experiments

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ABSTRACT

It has been noted since the mid 1800s that the Michelangelo's David, the standing marble male nude representing a masterpiece of the Italian Renaissance, is affected by small cracks on both legs that threaten its stability. Understanding the characteristics and the conditions under which these lesions developed is thus critical for the preservation of this universal masterpiece. In this study, we use an analogue modelling approach to test the conditions that led to the development of fractures in the David's legs and to get insights into its stability. Small-scale (10 cm-high) gypsum replicas of the statue were deformed in a centrifuge, where the models were affected by a body force stronger than gravity but otherwise playing the same role. Analysis of the model results suggests that both the stability and the resulting deformation of the statue are highly sensitive to its attitude. A forward inclination promotes destabilization: the higher the angle of inclination (α), the more unstable the statue becomes under its own weight, confirming existing FEM modelling. In a vertical position, rupture of the statue typically occurs in the lower portions of the legs, but ruptures tend to develop progressively higher along the legs as α increases. Comparison of these results with the lesions detected on the actual David suggests that a long-lasting, small forward inclination (likely close to $\sim 5^{\circ}$) of the statue may have represented a critical driving factor for the development of the observed damages.

1. Introduction

David is a marble statue of a standing nude male carved between 1501 and 1504 by Michelangelo Buonarroti. It represents a masterpiece of the Italian Renaissance, and because of this value, the preservation and the stability of the statue have been the focus of several analyses in the last centuries. Special attention has been paid to the several hairline cracks that characterize both the left ankle and the lower part of the tree trunk supporting the right leg of the statue (Fig. 1; see also [1,2]). The cracks were first detected between 1852 and 1872, and nowadays they are more extensive than in 1872; however, there is no description of the evolution of damage in the period between 1872 and 2003, when the statue was subjected to another detailed analysis [1].

In the last decade, the preservation state of the Michelangelo's masterpiece has been accurately monitored and evaluated by means of photogrammetric studies [3], finite element (FEM) analyses [2,4], high-resolution 3D scanning [5,6] and in situ fracture monitoring through fibre optic Bragg gratings [7]. These studies have shown that in its current vertical position – i.e. with the basal plinth horizontal – the David's centre of gravity does not coincide with the centre of gravity of the base, resulting in an eccentricity of the loads [2,5] (Fig. 1). In spite of this eccentricity, recent FEM analysis [2] suggests stability of Michelangelo's David in its current position and also puts emphasis on the major role played by a forward inclination (from 1° to 3°) of the statue on the development of the cracks in the ankles [2,4]. Such an inclination was likely produced during the exposure of the statue in Firenze (Italy) in front of Palazzo Vecchio (1504–1873) due to the uneven subsidence and rotation of the statue's foundations [2]. However, the David was inclined in other occasions during its life, for example, during its transfer (1873) to the current position in the Galleria dell'Accademia.

2. Research aims

We describe the results of an analogue modelling study, in which small-scale replicas of the Michelangelo's David were deformed in

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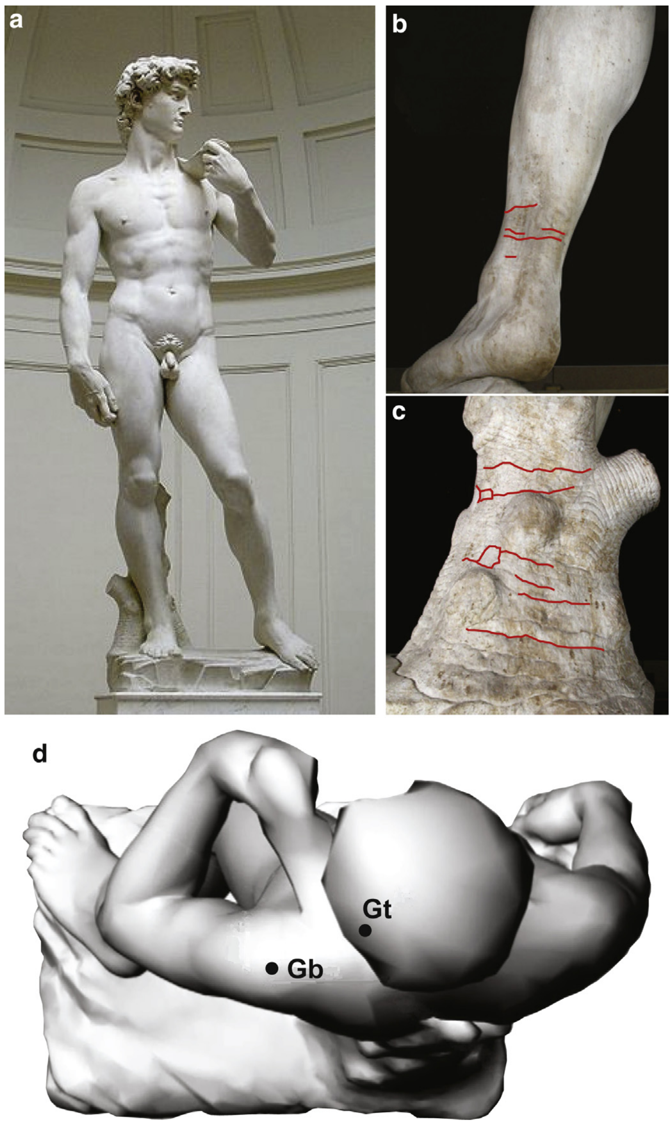

Fig. 1. (a) Michelangelo's David and (b, c) details of the fracture system affecting the lower sections of the statue's legs [2]. Behind the right calf of the statue is visible the so-called "trunk", which was positioned by Michelangelo to improve the static stability of the statue; (d) top view illustrating the projection of both the centre of gravity of the masses (statue + base) (Gt) and the centre of gravity of the supporting base on the ground (Gb). Note the non-correspondence between the two points, with resulting eccentricity of loads. Modified after [2,5].

a centrifuge, with the aim of analysing the conditions leading to the fracturing of the David's legs. Particularly, the current experiments were mostly aimed:

- to analyse geometrically the volumes of the statue subjected to highest stresses;
- to verify the boundary conditions under which the position of these volumes vary along the statue;
- to attempt to extrapolate these inferences to the actual David.

To this aim, we adopted the conditions that may have led to the mentioned fracturing of the statue by exploring variable degrees of forward inclination (from 0° to 25°) with respect to the current vertical position. To our knowledge this modelling approach, which is complementary to numerical (finite element) modelling, is the first application of centrifuge analogue modelling to the study of the Michelangelo's David and other statues in general.

3. Centrifuge modelling

Centrifuge analogue models have been widely used in the last 50 years to reproduce and investigate a variety of geological, geotechnical and engineering problems [8,9]. In particular, the centrifuge technique has been proven to represent a valuable tool to investigate complex stability problems, with applications in the field of Cultural Heritage, including the stability of leaning towers, the leaning tower of Pisa being the most famous example [10]. The use of this technique is based on the observation that a correctly scaled analogue model represents a realistic replica of the natural (real) prototype and it is subjected to an evolution which simulates exactly that of the original (the prototype), though on a more convenient geometric scale (smaller) and with a conveniently changed time scale and deformation rate (faster) [8,9]. Given the significant decrease in size of the studied sample and the different time-dependent evolution of the deformation dynamic, a correct scaling requires the physical characteristics of the materials employed to be correspondingly rescaled [11]. In particular, if small-scale models are exposed to the same gravitational acceleration as the full-scale structures, the use of models made of very weak materials is needed to reproduce natural processes in which gravity plays a controlling part [8,9,12]. With such weak and soft materials, it is normally impossible to construct models and study the resulting deformation. However, if the models are affected by a body force substantially stronger than gravity but otherwise playing the same role, their building materials may not be necessarily weak and soft: the obvious force well suited for such a role is the centrifugal force [8,9].

3.1. Experimental set-up

The experiments were performed by using the centrifuge apparatus at the Tectonic Modelling Laboratory of the Institute of Geosciences and Earth Resources (National Research Council of Italy) settled at the Earth Sciences Department of the University of Florence (Fig. 2). The original 410 cm-high David was reproduced by small-scale (10 cm-high) replicas built in commercial hemihydrate gypsum ($CaSO_4 \cdot 1/2H_2O$) mixed with water. The mixture has been poured into a silicon mould, allowing the hardening of the model; an ultrasound vibrator was used to minimize air bubbles trapped inside the mixture [13]. Gypsum was chosen in our modelling approach because it is easy to find, cheap, and can be easily moulded; its rheological properties approximate those of the Carrara marble used for the David (see below). We tested other solutions to perform the models (e.g., small-scale David made of marble powder mixed up to variable amounts of synthetic binders) but they did not provide a reproducible rheological response and were thus discarded.

The small-scale statues were allocated inside the internal rotor of the centrifuge in a pendulum system, which – during a centrifuge run – rotated in response to centrifugal body forces (Fig. 2). In such a system, the models were subjected to a force field exactly mimicking the gravity forces in nature [8,9]. Each run consisted of a phase with increase in angular rotation rate to achieve a chosen acceleration value, which was maintained for at least 45 s, and then of a phase of deceleration to normal gravity conditions. The different experiments consisted of several centrifuge runs in which the peak velocity was progressively increased up the rupture of the statue. In these conditions, the statue became increasingly "heavy" in the field of rising centrifugal acceleration until the gravitational stresses exceeded the material strength and failure occurred.

In the standard procedure, the gypsum model was positioned vertically in the centrifuge (i.e., with a horizontal basal plinth) and the velocity of rotation was progressively increased in successive runs with increments of 50 revolutions per minute (rpm) until