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Stability of megalithic structures against overturning

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ABSTRACT

When restoration works are carried out on a megalithic monument, the study of the structure's stability is always a significant task. In this paper, the overturning stability problem regarding megalithic structures is presented. Classical and advanced theories are implemented in a computer program to obtain the orthostat's overturning safety factor. Two examples of application concerning polylithic and monolithic structures are explained. These cases show the capabilities of this code to deal with current orthostat stability problems. Moreover, the program is able to support simulations on constructive processes and methods of erection or even to study the possible orthostat breakage causes. This information can contribute to a better knowledge of ancient constructional technology, which is directly connected with the cultural heritage of prehistoric societies.

1. Introduction and research aims

1.1. Introduction

A megalith is a large stone that has been used to construct a structure or monument, either alone or together with other stones. The word "megalithic" describes structures made of such stones, utilizing a connecting system without the use of mortar. The construction of these structures took place mainly in the Neolithic and continued into the Chalcolithic and Bronze Age. The types of megalithic structures can be divided into two categories: the Polylithic type and the Monolithic type. The most common type of polylithic construction in Europe is the portal tomb. Generally known as *dolmens*, a portal tomb is a chamber consisting of upright stones (orthostats) with one or more large flat capstones forming a roof. Many of these, though by no means all, contain human remains, but it is debatable whether the use as burial sites was their primary function. It is assumed that most portal tombs were usually covered with earth or smaller stones to form a barrow. Nevertheless, in many cases, that covering has weathered away, leaving only the stone "skeleton" of the burial mound intact. Most of these constructions date from the early Neolithic period (4000 to 3000 BC). The second-most-common tomb type is the passage grave. It normally consists of a square, circular, or cruciform chamber with a slabbed or corbelled roof, accessed by a long, straight passageway, with the whole structure covered by a circular mound of earth. Sometimes it is also surrounded by an external stone kerb. Finally, there is another type known as gallery graves. These are axially arranged chambers placed under elongated mounds.

The classical example of monolithic monument is the single standing stone, or menhir. Their size can vary considerably, but their shape is generally uneven and squared, often tapering towards the top. In parts of Britain and Ireland, the best-known type of monolithic construction is the stone circle [1].

Frequently, restoration projects of megalithic monuments require stability studies to avoid possible collapses due to excavation or relocation of the orthostats. Moreover, architectural works in the area surrounding the megalith construction may demand stability and mobilization analysis to achieve favourable environment conditions for its conservation [2]. There is a lack of simple numerical tools to deal with megalith stability problems. Many of the codes existing in the literature are related to wall design and they are usually either complex to use [3] or they just implement classical approaches. Sometimes these classical proposals cannot be adapted to the real problem because of its limitations [4] or they are simply an inaccurate option.

On the other hand, the development of technical tools can be useful to researches on cultural heritage in order to assess ancient cultures' studies. These works, focussed on the different aspects of the ritual and beliefs of the builders, can go into detail about

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the huge effort they spent in megalith constructions and the great technical challenge they faced.

1.2. Research aims

In this paper, civil engineering connects to archaeology to develop a computational tool designed to determine the stability of megalithic orthostats against overturning. This program includes the possibility to carry out a classical Coulomb Theory calculation as well as a Log Spiral Theory calculation based on a kinematical approach [3]. The code provides the overturning safety factor, taking into account the weight of the orthostat, the wind action, possible restoration loads and the soil cohesion effect. Two real cases of application on megalithic structures are described at the end of this paper to show the different software capabilities. The software applications are pointed not only to avoid stability problems during restoration works, but also to support research studies on the Neolithic cultural heritage.

2. Stability calculation methodologies

Active and passive earth pressures play an important role in soil-orthostat interaction. Maximum active and passive pressures can be computed using the well-known Rankine, Coulomb and Log Spiral earth pressure theories, with their advantages and limitations. Rankine Theory is the simplest method but has important lacks: first of all, the friction angle at the soil-orthostat interface, δ, is assumed to be equal to the inclination of ground surfaces. Moreover, it can be applied only to simple conditions, i.e. planar ground surface, uniform surcharge and homogeneous soil. On the other hand, the main disadvantage of the Coulomb Theory consists of assuming that the passive pressure failure mechanism involves sliding along a plane surface. As a result, values of the passive earth pressure coefficient, K_p, are too high when the value of δ is larger than 0.4 times the angle of internal friction of the soil, ϕ',which is very usual in most cases.

Finally, the Log Spiral Theory uses a curved failure surface which represents a more probable failure mechanism for values of δ larger than $0.4\phi'$. The main Log Spiral limitation is that a computer program is needed [4]. Both Coulomb and Log Spiral are upper bound theories of limit analysis. Therefore, the smaller the value of K_p, the more accurate they are.

In program *Orthostab*, both methodologies are implemented, and the Log Spiral Theory was approximated by a simple method proposed by Soubra and Macuh [3]. This simplified approach is based on rotational log spiral failure mechanisms in the framework of the upper bound theorem of limit analysis for the general case of an inclined orthostat and a sloping backfill. Considering that the energy balance equation of a rotational log spiral mechanism is equivalent to the moment equilibrium equation about the centre of the log spiral, a numerical optimisation of the active and passive earth pressure coefficients was performed [3].

2.1. Coulomb theory

The Coulomb active and passive earth pressure theory assumes that a soil wedge with a failure plane making a critical angle θ_{cr} with the horizontal is in a condition of incipient failure, as shown in Figs. 1 and 2. In the case of the active pressure problem, the intact wedge is about to slide down the failure plane, thus generating active earth pressure against the orthostat. In the case of passive condition, Fig. 2, the critical wedge is about to slide up the failure plane, thus generating a passive earth pressure against the orthostat. From statics, the wedge can be treated as a particle that is subjected to three coplanar forces, W, P (P_a or P_p) and R, where

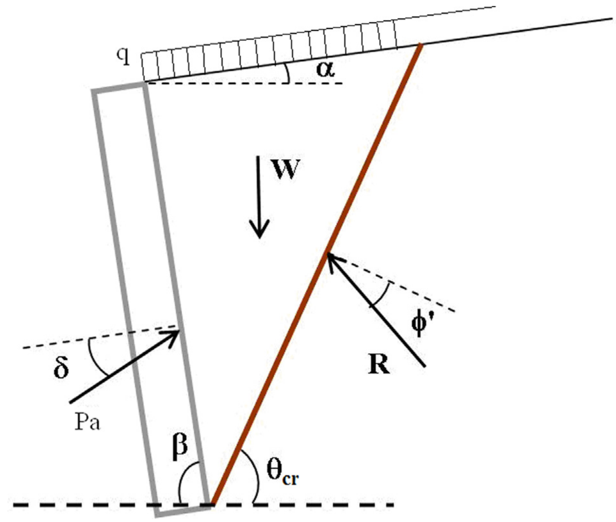

Fig. 1. Coulomb failure mechanism for active earth pressure analysis.

W is the self-weight of the wedge, P is the resultant of the orthostat reaction against the soil, and R is the soil reaction against the sliding wedge. The force P makes an angle δ with the normal to the back face of the orthostat (the face in contact with the tumulus, in the case of a portal tomb), which is the orthostat-soil interface friction angle. On the other hand, the force R makes an angle ϕ' with the normal to the failure plane, which is the internal friction angle. Finally, q is the vertical surcharge loading.

The Coulomb active earth pressure coefficient for the general case shown in Fig. 1 is dependent on the angle of the back face of the orthostat, β, the soil-orthostat friction and the angle of backfill slope, α:

$$K_a = \frac{\sin^2\left(\beta + \phi'\right)}{\sin^2\beta \sin\left(\beta - \delta\right)\left[1 + \sqrt{\frac{\sin(\phi'+\delta)\sin(\phi'-\alpha)}{\sin(\beta-\delta)\sin(\alpha+\beta)}}\right]^2} \quad (1)$$

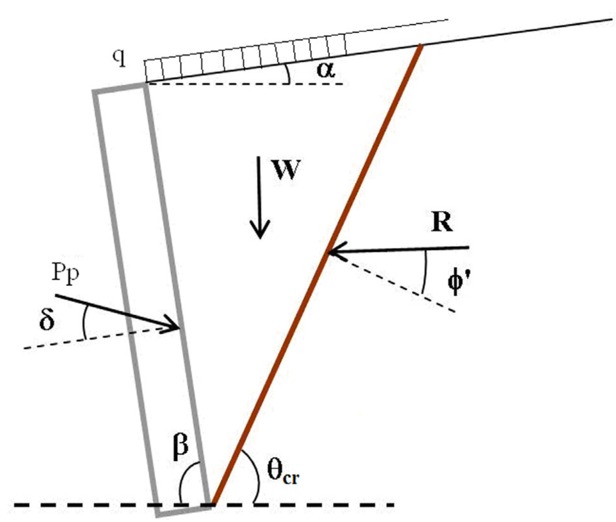

Fig. 2. Coulomb failure mechanism for passive earth pressure analysis.