GEOTECHNICAL TECHNOLOGY IN ANCIENT PERUVIAN FOUNDATIONS

TECHNOLOGIE GEOTECHNIQUE DANS LES FOUNDATIONS DU PERU ANTIQUE

A. Carrillo-Gil

Professor Emeritus
National University of Engineering, Lima, Peru

SYNOPSIS

Information is presented on the study of Peruvian Historical Geotechnics, ongoing during thr course of several years. The use of soil and rock asconstruction materials is examined, as in their utilization for supporting the monumental works of the ancient pre-hispanic South American peoples. The reduction of contact pressure transmission is analysed, and the effect of seismic phenomena on adobe walls with gravel and cane placed in layers at different levels is also considered. A quasi-static analysis is adopted for the stress distribution, and this is verified by means of tests on reduced-scale geotechnical models. A study is made of the foundation technology of the ancient works constructed by the Peruvians of long ago whose inventiveness led them to achieve structural stability by the employment of an adequate drainage system to provide protection from the adverse effects of humidity.

INTRODUCTION

The birth of civilization on the American continent took place some 4000 or 5000 years ago on the Peruvian coast,according to recent studies, It has been shown that the oldest sites located to the west of the Andes antedate by some thousands of years the sites in Central America which were traditionally considered the birthplace of civilization in America. While the early Peruvian Andean cultures never attained the levels of the ancient Mesopotamian and Egyptian civilizations, the expertise and skill shown in the building of large structures, the organization of labour, artistic merit, and political system demand a favourable comparison with their Old World contemporaries.The ancient Peruvians, as the oldest civilization in America, started out close to the sea and later moved quite suddenly to the Andean highlands. Here they built up a flourishing economy, based mainly on agriculture which did very well at more than 3000 m above sea level despite climatic conditions, earthquakes and other phenomena typical of the South American Andes. The deepest roots of this culture date from much earlier than the Spanish Conquest, and it has left us, by virtue of its structures, irrespective of their uses, a monumental vision of long-ago Perú and of a part of the history of Humanity.

Pre-hispanic civil engineering works with their extraordinary variety and dimensions are the legancy of these engineers of the ancient world. They developed their projects well and put them into pratice using locally available rock and earth in the construction of housing and other basic necessities of the society, such as agricultural structures, temples and defence works.

The customs and traditions of the ancient Peruvian peoples where never documented owing to the lack of writing. The Spanish conquerors found our civilization flourishing, but they destroyed much of the native building and technology in their lust for gold and the desire to impose religion (Sowers,1979), The lack of a formal mathematical system and the absense of writing impeded a greater development of pre-hispanic technology. However, despite all these circumstances, the ingenious ancient Peruvians where able to solve a variety of engineering problems which has enabled their works on the Peruvian coast, dating from 2500 BC, to possess a natural stability evidenced by their existance today, despite the ravages of climate and of strong seismic activity characteristic of the area.

All this has led us to study the pre-hispanic works from a purely engineering poin of view, specificaly from the geotechnical angle, but without forgetting historical aspects, geographical development, morphological and historical considerations cogent to their inception and construction. In this way it is possible to establish a probable behaviour for these structures,according to scientific and technical concepts, and to apply this to engineering techniques for present-day restoration.

STRUCTURES AND FOUNDATIONS IN ROCK

The most important pre-hispanic Peruvian works in rock are to be found close to the city of Cuzco, in particular in the fortress of Machu Picchu, built on the eastern slopes of the Andes (Fig. 1). The zone is traversed by geological faults, the behaviour of which was known to the ancient Peruvians.This knowledge is demostrated by the way in which the buildings are distributed in sections to provide a certain flexibility and

Fig.1 Pre-hispanic constructions in stone MACHU PICCHU archaelogical site, Cuzco, Perú

thus avoiding adverse seismic effects on the rock structures. The fortress, as in the case of others situated in different parts of Perú, had good surface and deep drainage systems. This has allowed the greater part of the foundations to have remained intact after centuries of exposure to inclement weather and to seismic phenomena. During the time they were in use ,these structures were constantly maintained, especially the drainage systems, but subsequent neglect has led to some differential movement along temple walls which cannot be attributed to geological movements or active faults. The foundation supports found in these areas are generally on rock, but there are also structures supported directly on soil, sand o gravel. Some of the latter are built in zig-zag fashion right up from the supports, thus achieving a secure hold in the soil or rock and avoid the effects of horizontal loading during the seismic movements which have been taking place in this area during many thousands of years (Fig. 2).

The rock employed varied according to type of structure, which generally depended on the use for which the building was destined. Relatively small stones where used in the building of the palaces, while the refuges and fortresses were constructed with gigantic blocks of diorite , porphyry or granite. In all cases the stone foundations have performed satisfactorily during many centuries except for a few examples where the foundation supports have suffered from dampness owing to a lack of drainage. Even in these cases, where there have often occurred considerable movements or angular distortion, there has not been a total collapse of the wall, but rater a disalignment of blocks from their original positions.

STRUCTURES AND FOUNDATIONS OF SOIL

Soil, like stone, is in the most anciently used of construction materials. Since the time Man ceased to lead a nomadic existence, and started to cultivate the land, he began to discover that the aerth could be moulded and dried in the sun, thus supplying him with a simple element of construction. In our era there is impressive evidence of Peruvian pre-hispanic soil structures such as those at Pachacamac, Pacatnamu, Moche, Cajamarquilla, Paramonga and Chan Chan - the latter considered the world's oldest city constructed from earth - to mention but a few. These examples are monuments which have survived the adversities of time and seismic activity.

We have mentioned that the predominant construction material used in the Andes was stone. However, this does not exclude the use of earth and mud in the Peruvian highlands. Similarly the preference for the use of the latter materials on the Peruvian coast does not preclude the use of stone for the bases of walls in the coastal regions.

In the manufacture of earth building blocks two processes can be defined : moulding or hand modelling. For moulding, wood or cane moulds are employed, whereas modelled blocks are simply fashioned by hand. In either case, the artisans' finger-prints can be seen on the blocks, evidence that the material was compacted and that the makers of these blocks knew their raw material. (PNUD, UNESCO, 1970).

Fig. 2 Stepped foundations in stone for the absorption of seismic movements, Cuzco, Perú

The adobe walls of ancient Perú are generally thick, and adapted to the existing topography. Augmented stability was conferred to the these walls by a slight inward slope, and these trapezoidal sections can be clearly seen today, both in the walls and in the individual building blocks. The most notable feature of these pre-hispanic walls is their height to width ratio which endowed them with considerable resistance. (Fig. 3).

Fig. 3 Pre-hispanic buildings in the adobe brick CHAN CHAN, Trujillo-Perú

The foundations of these monuments were usually simple. Some sources of information of pre-hispanic origen which refer to block-built walls indicate that these were placed on a rough foundation of stones at ground level. The excavations for this work were filled with compacted earth and medium-sized stones. The width and depth of these excavations was never greater than the width of the base of the wall. The principal reason for this is that these structures are to be found in some cases on rock outcrops and the others on loose soil. The majority of the foundations follow the contour of the ground. The lower portions of the walls were constructed with a larger width than the following level in trapezoidal form so that the pressure transmitted to the supporting soil was reduced. In all cases knowleage of the foundation soil was shown for the better or worse support of the structures, while the deepening of the foundations was avoided owing to religious or mythical beliefs. (Carrillo Gil, 1988).

INVESTIGATION CARRIED OUT

From the whole range of types or pre-hispanic wall, we have selected for this study walls constructed principally from adobe brick and which have layers of straw, cane, small stones and rock at different levels in the wall. By this means a better load distribution is achieved at foundation level. We have also set out to establish whether tnis type of structure is capable of absorbing strong seismic movements. In order to make a quasi-static analysis of the stress distribution in a typical pre-hispanic wall of the nature described above, the following calculation hypotheses have been adopted : a pyramidal pressure distribution is assumed in a model whose dimensions represent the average of a large number of walls studied in the principal Peruvian archeological sities. The inclination of the pyramidal pressure distribution is taken as an average of 2°, theoretically equivalent to the classical value of the angle of inclination of the shear planes if the adobe block were punched under loading. This is :

$$\alpha = \frac{\pi}{4} - \frac{\varphi}{2}$$

assuming an average of tan α = 0.6 according to experimental and theoretical considerations. A two-dimensional analysis has been used (Fig. 4)

Thus, for this mathematical model, calculations have been made on the loading formulae at three different levels produced by the adobe blocks I, II and III respectively, assuming that the blocks II and III transmit the load downwards according to a pyramidal pressure distribution, with a load distribution angle α . At the foundation level, the contact pressure is given by the equation:

$$P_f = \Gamma\left[\frac{1}{d} \left(\frac{c+d}{2}\right) h_3 + \frac{\left(\frac{a+b}{2}\right) h_1 + \left(\frac{b+c}{2}\right) h_2}{(c+2h_3 taga)\,(1+2h_3 taga)} \right]$$

which shows up the effect of the stone and cane reinforcements in the adobe wall as a reduction in the vertical pressure at the foundation in up to 36 %, this is something over one third less than the pressure transmitted to the foundation by a similar structure were the stone and cane layers are omitted.

As the object of the study was to determine the effect of the horizontal reinforcements in pre-hispanic walls of adobe on their resistance to horizontal and vertical loading, several reduced-scale adobe specimens were employed in tests. The natural-sized prototype was selected after a thorough study of different types of existing pre-hispanic walls.

The material used for the formation of models for this study was pre-hispanic adobe of an approximate age of 2000 years, taken from walls dating from as far back as 300 BC.

The mortar used to lay the small adobe blocks was made from the same mud as the blocks themselves, and the canes used as horizontal reinforcement were of approximately 1 inch in diameter. These were split and crushed between the adobe blocks.

After drying each of the specimens during 30 days, they were tested in axial and lateral compression, with a gradual increment of loading

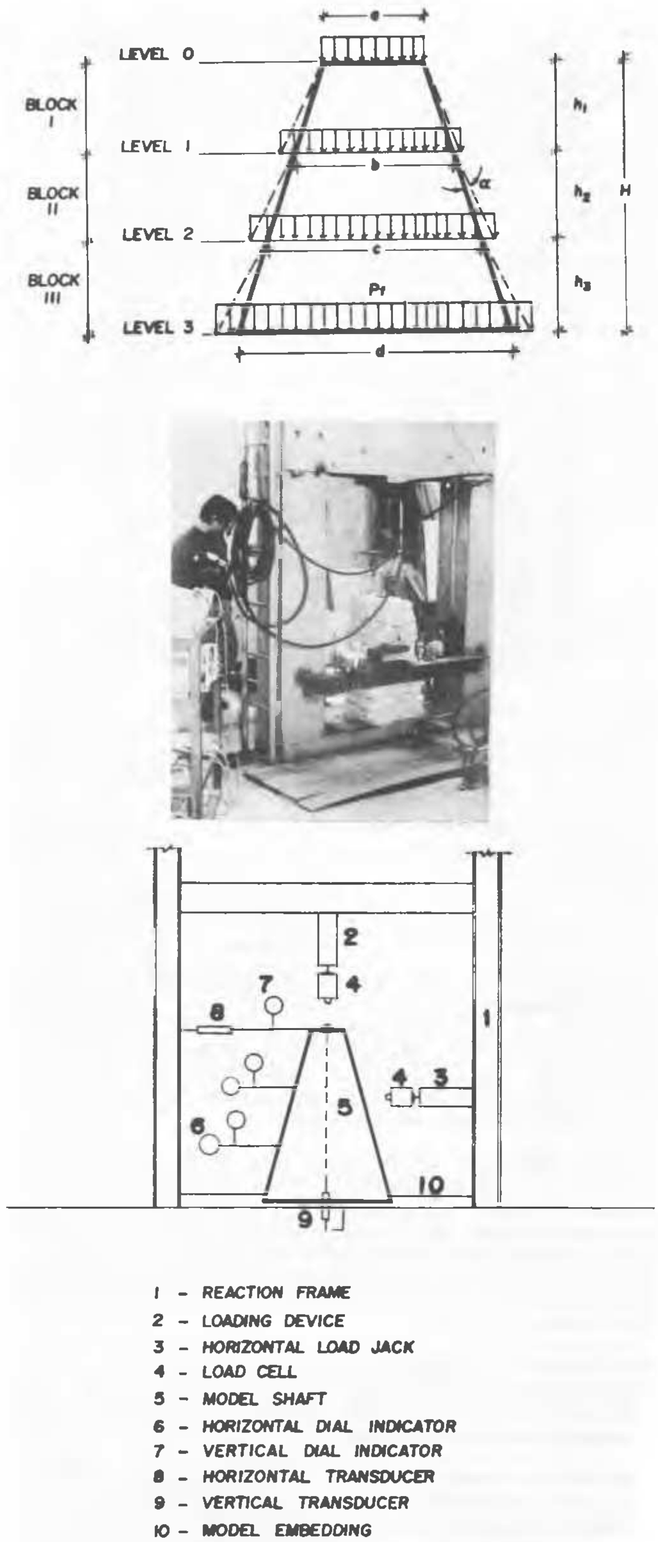

Fig. 4 Outline of theoretical model and small-scale testing system.

until failure. This confirmed the predictions derived from the mathematical model proposed : there is a substantial reduction in the pressures at the base of the foundation when straw, canes and small stones are placed into the wall at different levels.(Carrillo et al,1992). This is one of the reasons why the considerable pressures transmitted to the ground by these historic buildings of adobe construction have been well borne by the foundation soils, something which is not true in other parts of the world, as indicated by Kerisel (1985), who states that numerous structures of ancient origin in Europe and Asia have not survived to the present day owing to great acting pressures (500 to 1000 kPa in the large Egyptian pyramids), which have caused serious damage, inclination and important settlements in those structures.

With reference to resistance to seismic phenomena involving lateral loading on these walls, it is suggested that a part of the seismic resistance of adobe block structures is related to the micro-fissuring of the mortar due to contraction during drying. It is thought that to achieve a resistant wall, not only is a strong material required but also a satisfactory performance of the block/mortar structure as a whole.

During the horizontal load test, in the case when the unembedded basis was considered (that is to say, when the walls are placed directly over the ground surface), the small wall failed by overturing about the toe in the moment in which the horizontal load yielded a moment equal to the resultant of the tensile stress,separating from the basis and forming a fissure along it.

The main structural faults in this kind of walls are due to flexure in the normal direction to its plane and tensile stress level, which produced fissures in their extremes and in the last overturning observed. In the case of embedding by the basis, the shearing was produced because the wall received horizontal loads in its plane.Diagonal craks were formed by the excessive shearing stress between blocks.

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