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Structural analysis for the restoration of the walls of Urbino

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ABSTRACT

The solution of many engineering problems are today found with the help of finite element models. The applications of this method assume, in general, an elastic behaviour for the finite elements. Where the real behaviour exceeds the elastic limit an alternative method must be adopted to take account of the non-linear behaviour. An example of the application of this method of structural analysis is found in the strengthening project of the walls of Urbino, based on an extensive investigation program concerning the soils, the foundations, and the masonry structures. The results of the survey have allowed a mathematical reconstruction of the wall's geometry and a simulation of the different patterns of failure that have occurred.

INTRODUCTION

The walls of Urbino represent one of the most significant architectural characteristics of the city; the rich iconographic historical evidence shows their importance throughout history. The first documents of the construction of the walls come from the 16[th] century; others record various restorations, refacings and reconstructions following damage, up until the present day. However, today the walls are, in many ways, extensively decayed, with visible signs of damage and structural failure hence the repair works must be carried out rapidly. Studies have already been carried out and results obtained, for a consolidation project undertaken in conjunction with the Urbino City Council with the supervision of

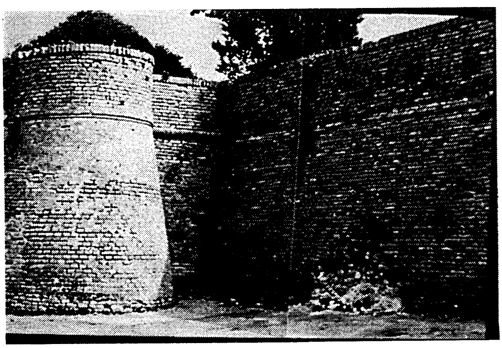

Figure 1

the Fine Arts Superintendent of Marche, utilizing the fields of historical research, petrography and topographical survey.

In order to ascertain the mechanical properties and geometry of the masonry, a program of investigations and experiments were developed, relating to a particular zone; the results were examined and the phenomena of failure were interpreted. The safety levels of the actual structure, as it stands today (chosen as a point of departure for successive definitions of consolidation interventions), are based on analysis carried out using 3D finite element models, taking into consideration the interaction of the earth and rocks behind the walls. The schemes were carried out utilizing the data obtained from the investigations into the soil stratification behind the walls, the geometry of the cross section of the walls and their rigidity and strength. On the basis of the available data, the examination of the phenomena of degradation, the numerous failures and damage present (which combined caused major failures) and the results of the analysis and investigations, it was possible to define the level of repair and strengthening.

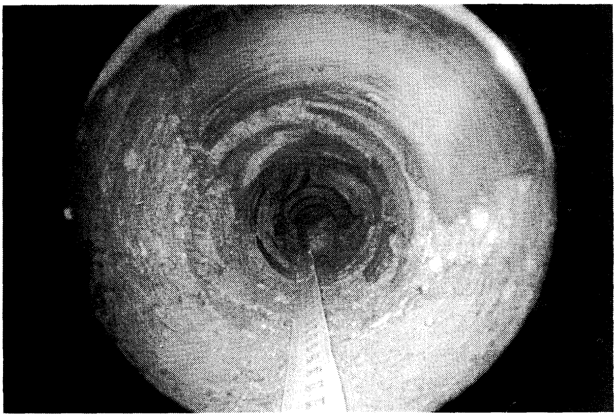

Figure 2

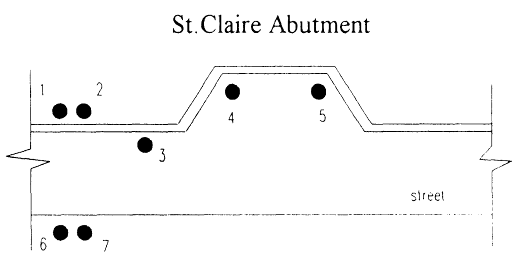

Figure 3 Positionig of boreholes

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THE WALLS AND THEIR DAMAGE

The walls have a total length of around 2770m; they are nearly all earth-retaining with the exception of one zone, which is 7m high and provides no earth-retaining function. Along the perimeter there are abutments which are often taller than the adjacent walls. The masonry consists of an external layer of brickwork, varying in thickness; within this layer there is an internal nucleus made of limestone or cemented lime marl, often the mortar has eroded from the joints resulting in the loss of bricks; in some zones, a different type of masonry consisting of striped stone blockwork is found. It is possible to distinguish phenomena of degradation of the material and static failures within the walls. The degradation of the materials is centred on the mortar in the brickwork joints. The external bricks themselves have also suffered from degradation: in particular there is evidence of empty or insufficient connections between the various elements, this is also the case regarding the internal layers of masonry.
The phenomena of failure consist of cracks, out of plumb, sliding of bricks/blocks and deformations; they can be attributed to soil settlements, and hence the movement of foundations, and the thrust of the earth, particularly in the presence, of water; this is combined with the almost complete absence of efficient buttresses in the walls and the lack of drainage for both rain and ground water. These phenomena are occasionally combined with seismic action which is not rare in this area.

TESTS

A series of tests carried out on site near the St. Claire buttress in the initial zone of the "G" tract consistingof 16 endoscopic examinations with a boroscope (figs 2 and 3), 12 examinations with television probes and dynamic penetration tests.

From the examination of the materials, it was possible to reconstructe the stratigraphic situation of the wall. To understand the characteristics of the wall's foundations and of the different soils constituting the slope on which the walls are founded, 7 geognostic boreholes were made and some undisturbed samples were taken; these were subjected to free lateral compression and expansion tests, tests to determine the Atterburg limits and granulometric analysis.
Regarding the mechanical characteristics of the elements constituting the external parameter of the wall, tests were carried out to verify the effective state of the mortar, in particular dynamic penetration tests were carried out in-situ while indirect tensile tests were carried out in the laboratory.

CHARACTERISTICS OF THE WALL AND SOIL

Examination of the material coming from the investigations carried out has allowed us to reconstruct the present state of the wall and to outline some transverse sections as illustrated in figure 4.
In particular we can distinguish:

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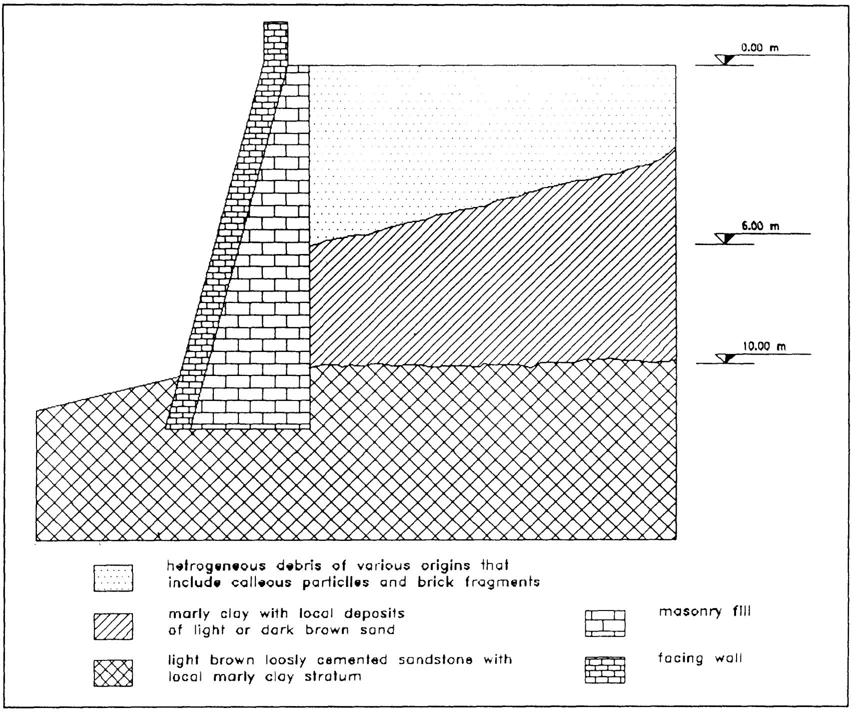

Figure 4

-the external wall consisting of flat-faced bricks of different dimensions, interconnected with pozzalònic mortar (around 0.40 m thick);
- masonry fill material, behind the facing, of variable thickness, from the base to the top;
The state of the facing wall varies according to the zone under consideration. In general phenomena of degradation, which provoked the collapse of this facing, were found.
The major degradation is concentrated in the mortar courses of the masonry joints. These phenomena can be attributed to weathering processes such as freezing-thawing, variations in temperature and humidity.
The bricks themselves also appear to have suffered from weathering effects.
The mortar was subjected to specific tests such as the dynamic penetration test which gave an average value of resistance of 0.9 MPa (notably inferior to the value for pozzolanic mortar in good condition), see figure 5.
These results were confirmed by the indirect tensile test carried out on samples extracted from the wall.
Regarding the masonry fill material, from the endoscopic investigation and the sonic testing carried out, it was found to be highly chaotic with the limestone, which constitutes the major part of it, loosely held together.
The soil behind the wall mainly consists of:
- heterogeneous debris for the first 6m;
- a layer of marly clay for 4m;

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- a substrata of loosely cemented sandstone.

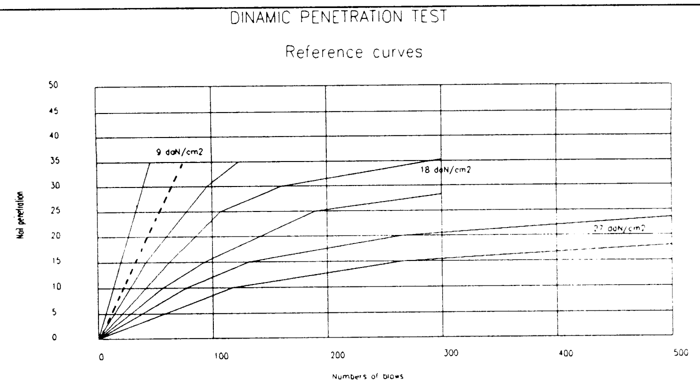

Figure 5

General soil characteristics are:

$w_l = 42.3\%$ $w_p = 19.8\%$ $I_c = 1.271$

$I_p = 22.5\%$ $P_s = 2.701\ t/m^3$ $s_r = 0.878$

REINFORCEMENT INTERVENTIONS

Many types of reinforcement intervention were foreseen for the Urbino walls. Firstly a method for lowering the water table by means of a drainage system consisting of holes in the wall which continue for some distance into the retained ground was suggested. This type of intervention allows the decrease of the pore pressures in the soils and consequently the amount of thrust.

The second intervention consists of tying the walls with traditional prestressed steel anchorages or synthetic ties, long enough to reach the strong strata. This kind of intervention makes the wall capable of resisting the forces acting upon it.

The alternative criteria foreseen comprise the construction of a new, independent retaining structure behind the wall, consisting of sheet piles of medium-large diameter, anchored at the top with prestressed ties. The new structure is designed to resist the total thrust.

MATHEMATICAL MODELS

On the basis of the data furnished by the investigations carried out in-situ and in the laboratory, various mathematical models of parts of the wall and of the St.Claire abutment were created (with the use of the calculation code SSAP implemented on PC), with the hypothesis of linear elastic rather than non-linear behaviour. This was carried out in order to verify the collapse mechanism and to evaluate the margins of safety following the foreseen interventions.

The non-linear analysis was made possible by the post-processor which follows an incremental elastic analysis. This post-processor is able to check, at every load step, the position of the representative point of the stress (of each finite element) with respect to the failure domain, in terms of principal stresses.

The failure domain of individual materials was defined by the tests carried out in the laboratory. In particular the situation of the wall prior to the interventions was examined by means of the finite element models.

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For the pre-intervention situation, a longitudinal section of a portion of the wall was analyzed for a force induced by the retained earth and a hypothetical water

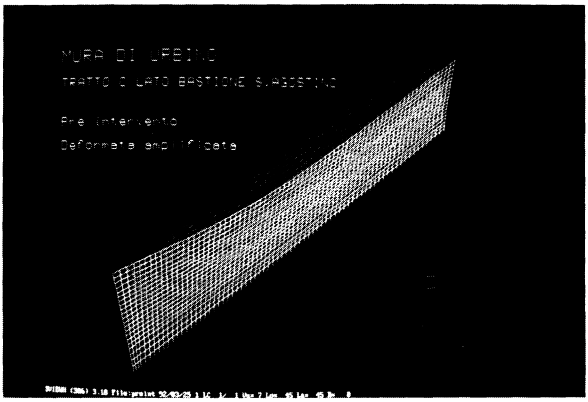

Figure 6

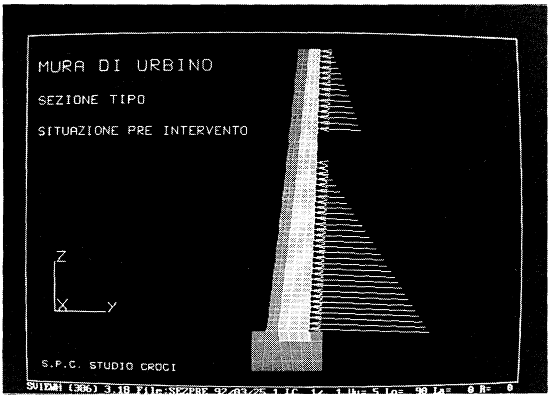

Figure 7

table coincident with the marly clay 6m below ground level. Figure 6 shows the model used and the amplified deformation.
The force induced at the base of the wall surpasses the admissable limits for masonry in the condition described above and justifies the phenomena of degradation found at the base of the wall.
A transverse section of the wall was then studied, again in the elastic field, in which the different materials that make up the wall were schematized, in particular the facing brickwork and the masonry fill (figure 7).
The action of the retained earth was schematized with forces concentrated at the nodes representing the resultant thrust of the retained earth and water table in the absence of a drainage system, on a unit length of wall.
Also in this case the external forces were too high to be equilibriated by the retaining wall.The analyses conducted in the non-linear field regarded a transverse section of the wall including a significant portion of the retained earth as shown in fig 8. The thrust of the earth in the lythostatic condition was simulated by applying the dead load in the vertical

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direction, while the forces on the wall due to seismic action were simulated by applying horizontal forces, proportional to the masses of the individual elements, in the direction of the axis (-y).

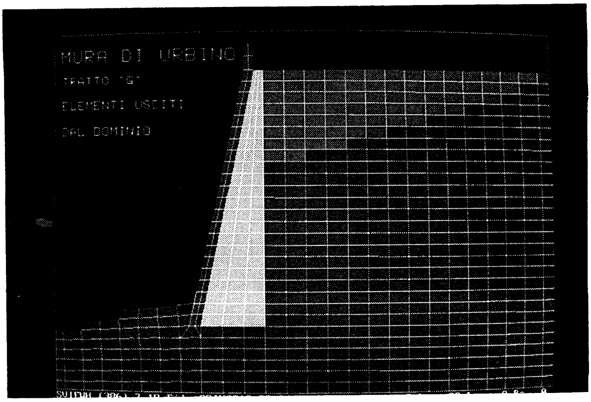

Figure 8

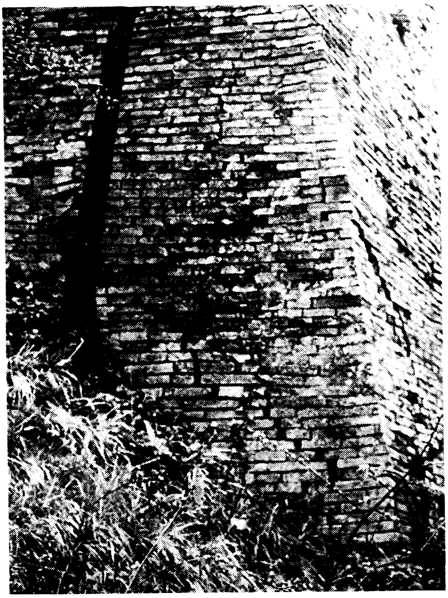

Figure 9

The elements that exit the failure domain identified the possibility of planes of failure congruent with the slip lines used for the calculation of the thrust in the analytical form.

Finally an elastic model of the St.Claire abutment was created. Given the geometric characteristics of the structure a three-dimensional model using "brick" finite elements with 8 nodes and elements representing the retained earth. The forces considered were the self weight of the wall and earth, and seismic action in the directions x and y. The observation of the stress showed a state of tension incompatible with the strength of the masonry, confirming the localized fractures found in-situ. In particular the localized cracks in the lower verticals of the abutment (figure 9).

Regarding the post-intervention condition, the longitudinal section was modelled, as for the pre-intervention case, with a reduced thrust from the lowered water table (2m from foundation level) and two ties (polypropilene, lightly prestressed), in accordance with the reinforcement intervention (see figure 10).

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A substantial reduction in the stress level at the base of the wall was found, as a result of the interventions designed, thus being compatible with the strength of the masonry.
A final analysis was conducted on the transverse section of the wall (see fig.11), with the interventions mentioned above. A substantially lower stress level at the base of the wall was also obtained in this case.

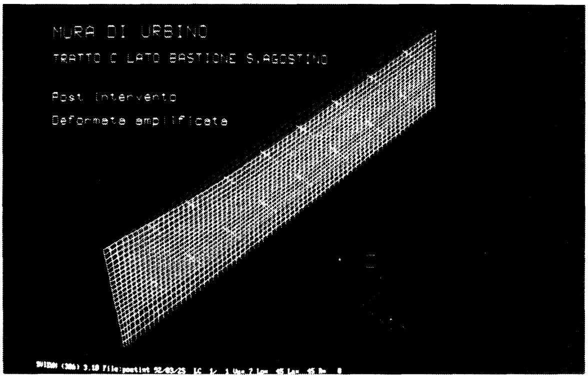

Figure 10

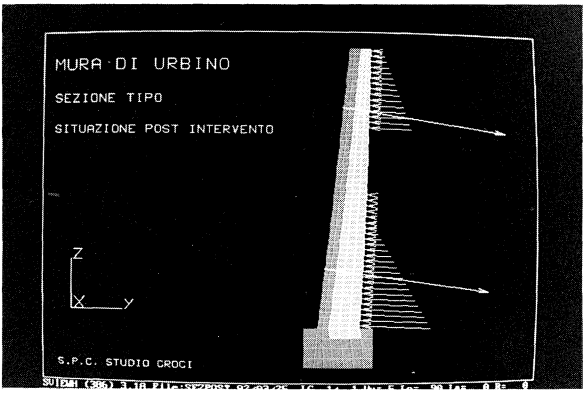

Figure 11

CONCLUSIONS

The program of in situ and laboratory testing on the different types of materials has allowed us to create mathematical models in order to recognise and simulate the various failure patterns of the walls.
Through this kind of "back analysis" it was possible to determine the actual values of the mechanical properties of the soil and masonry involved.
The models were also used to assess the reliability of the reinforcing intervention in order to evaluate the safety level corresponding to the different strengthening criteria.