An experience of a training team of structural engineers on archaeological consolidations in the Sultanate of Oman

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1. The consolidation works in UNESCO site of Khor Rori

1.1 Introduction:

The ancient city of Khor Rori (Salalah, Sultanate of Oman), was originated on about 4th century B.C. along the well known “Incense Route”; since 2000 is listed as World Heritage Site within “The Land of Frankincense”. The ruins are made up of irregular stone external layers and an internal chaotic mixture of ground materials. Large sections of the walls show marked signs of subsidence attributable to poor quality of the inner mixture and the lack of topside protection from the rain: these appear as surfaces collapsed into the spoon shape typical of the landslide mechanics of soil subsidence.

Since January 2005 programme of structural consolidation has been arranged, involving a group of young post-graduate engineers, during the archaeological campaigns directed by Prof. Alessandra Avanzini (Università di Pisa, Italy).

The work involve team members in several related field activities such as organizing the construction phases and supplying material and tools; forming the eventual young engineers coming for the first time, forming the not specialized manpower together with research studies and structural models of the behaviour of the walls.

The project and related activities have been set up within The Office of The Advisor of His Majesty The Sultan for Cultural Affairs and have been extended to the UNESCO site of Al-Balid (Salalah, Oman) since January 2007. The UNESCO archaeological site of Al-Balid, inside the World Heritage “Land of Frankincense”, is directed by Prof. Juris Zarins (Springfield’s Southwest Missouri State University, U.S.A.).

The complete list of the participants on the project:

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1.2 The structural problems

The ruins of the ancient city are bounded by walls of considerable thickness (up to 4 m.). The walls’ masonry as well as their infrastructures (towers, gates, entrances, etc.) and the dwellings within them are all made up of two poorly worked limestone or sandstone external layers without mortar joints. In their centres is a disorganized mixture of unselected ground materials, mostly sand and clay. The granulometric composition of such a random mixture ensures a certain degree of internal cohesion and shear strength during the monsoon rain season.
It is very likely that when the walls were built they were coated with plaster and some kind of topside protection against the rains. Such measures would have afforded cohesion to the walls, which are mainly of an “opus incertum” type, and prevent the filling material between the two outer facings from losing cohesion and being washed out. There are now large sections of the walls that show marked signs of subsidence attributable to the poor quality of the inner plaster mixture, exposing them to transverse earthquake collapses and the effect of the monsoon seasons, and the lack of topside protection from the rain. Essentially two types of collapse have been encountered:

a) expulsion of the outer facings caused by the transverse pressure exerted by the random inner clay-sand mixture, due to loss of cohesion and meteoric washout. These extrusions are visible as vertical bulges as well as rigid rotation of single bricks or groups of bricks starting at the top;

b) expulsion of the outer brick layers and the internal mixture of the thicker walls. These appear as surfaces collapsed into the spoon shape typical of the landslide mechanics of soil subsidence in presence of transverse loads, as earthquakes, joined with repeated monsoon seasons.
Both phenomena, which began after archaeological excavations were initiated and worsened with each monsoon season, have reached macroscopic proportions and manifest such a rapid and irreversible development that large sectors of the existing walls are now so damaged that there is a real risk of their collapsing within few years. The situation is compounded by further issues, amongst which the critical state of stability of the wall base should be noted. In fact, the bases in many sections manifest progressive thinning or thickening as a result of the lateral thrust of the ground materials within the brick masonry layers.

1.3 Guidelines for consolidation.

Given the structural damage to a number of the walls in question and the impossibility of onsite reinforcement without significantly altering their constructional and aesthetic features, the only course of action is to carefully dismantle and rebuild them. One critical consideration is that the extreme precariousness of some of the walls constitutes a very real risk for visiting tourists and scientists alike. In order for reconstruction to be carried out properly, that is, by replicating the original techniques, particular attention must be focused on the nearly perfectly preserved residues of mortar in the joints between some stone blocks. As far as possible, rebuilding should adopt the same mixture, design and chromatic effects as the originals.

These were presumably prepared in underground ovens to produce quicklime (CaO), which was then slaked by soaking to produce Ca(OH)$_2$ (also known as lime putty), which when mixed and left to hydrate yields limestone (Ca(OH)$_2$ + CO$_2$) = CaCO$_3$ + H$_2$O). There is much evidence supporting the utilisation of this procedure, in many ways similar to age-old building techniques used elsewhere, including Europe.

In order that the structurally damaged walls be rebuilt in accordance with UNESCO guidelines, taking into account the construction’s geometrical and historical features, intervention should proceed as follows:

a) **Reducing the internal transverse loads**, by way of partial calcification of the inner random mixture in order to afford it permanent cohesion. This can be achieved by adding a low percentage of lime mortar, similar in composition and colour to the residues examined, together with random stone filler to reduce the percentage of clay and increase the internal friction properties of the inner mixture. This will lessen the horizontal load on the external brick layers. Furthermore, wherever possible, more stone slabs should be placed crosswise, as “orthostats” to connect the external layers and prevent bulging.
b) *Preventing rain seepage from the top* by protecting the upper part of the walls through addition of a layer of “poor lime mortar” to form a suitable deck laid with a slight camber (a slope of 1-2%) on both sides to allow rainwater runoff. This layer can be finished with a mixture of stones and sand designed to yield the same colours as the walls (beautification).

c) *Preventing lateral washout of the internal mixture* by sealing the interstices between the non-squared stone blocks with the same lime mortar used for beautification. The mortar should, as far as possible, be applied under the cut (back from the wall surface) to reduce its visual impact.

![Figure 3. specimens of mortar mix design and small test walls for rebuilding procedure.](image)

Particular attention is to be given to an area currently shored up by tubular scaffolding against a wall where, parallel to the level of the supports, one of the two external layers has largely given way and which in turn shores up another wall at right angles to it (via the upper plate of a horizontal metal support), which itself presents a vertical bulge as well as displacement at the base (Figure 5). Here, on-site reinforcement will be necessary both to secure the walls and to permit subsequent reconstruction of the collapsed facing.

### 1.4 Work programme

Firstly, a series of wall and mortar samplings was conducted to establish the design for the mortar mix, including definition of the appropriate composition and any additives necessary to achieve the desired colours. The wall was then dismantled, the blocks catalogued and then reassembled, beginning with a large isolated section of wall to test out the procedure. The outer facings have been carefully reassembled in their original positions, the only modifications being some limited filling to bridge any gaps after a layer of geotextile was laid to mark the completed portions. To reduce the amount of clay as much as possible, the filler material has been altered by adding a mixture of sand and
rubble found locally and inserting some transverse stone courses to establish an effective connection between the two faces. Lastly, the top of the newly consolidated walls were protected with a low-gravel-content layer of sand and gravel laid with a slight convexity in order to allow rainwater to flow off toward the edges of the wall.

The entire programme was executed by workgroups consisting of young, newly-graduated engineers: they were assigned not only of the task coordinating the crew’s work, but of managing the details of the construction site logistics themselves, including the materials and equipment supplies. As the operations were carried out in a low-tech context, in which the only readily available resources are a workforce of willing, but unskilled Pakistani, Egyptian and Indian labourers, and the not particularly well-stocked stores and small craft shops in the city of Salalah, the job revealed to be a true exercise in inventiveness for the young engineers, calling for continuous ingenuity to resolve the most disparate problems - hardly ever encountered in these productive reality (Sassu et al – 2006).

2. The consolidation works in UNESCO site of Al Balid

2.1 Generals

In the meaning time, members of the engineering team group has been involved to the consolidation of the Fortress of Al Balid in Salalah erected about 1100 A.D., in an excavation process managed by the Institute of Archaeology of the Missouri University. In this case no mortar has been used for bearing walls, while the resistance was ensured by the gravity loads of the walls and an efficient washing out of the rains through the walls and by the use of small stones to fill in the irregularities of the block joints.
The fortress is composed by a texture of dry stone walls partially collapsed or covered by sand and lime. The construction is organized on a rectangular plan of about 70x60 meters, with circular towers on the edges and near the gates. The structural consolidation works has been started in early 2007 and has been divided into two main categories:

1. Stone and earth ramps.
2. Local reconstructions of collapsing masonry panels.

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2.2 **Stone and earth ramps**

Eight stone and earth ramps has been individuated around the external walls of the fortress, made intentionally during previous works or caused by natural deposit due to environmental effects. It has been necessary to remove the ramps to show the original walls, avoiding an unbalanced excavation (exterior-interior); moreover some ramp could be precious to remove materials from the inner part of the fortress. One of them has been completely remove, except a zone of respect in front of the fortress, to prevent rotation collapse of the perimeter walls of the fortress. On north-eastern edge
new ancient structures of masonry walls (maybe pre-Islamic) has been discovered under a round tower. Another has been partially removed, conserving a path of about two meters to penetrate inside the fortress and maintaining a zone for respect similar to the first one. Two ramps, artificially erected in the past to take away the stones of the construction, had been strongly reduced in length, to permit the restoration of the adjacent wall zones and to prepare the access along the main gate of the fortress.

2.3 Local reconstructions of collapsing masonry panels.

It has been individuated and restored typical local collapsing zones on external walls, situated in the southern and in the eastern sides of the fortress. The reconstruction phases has been arranged starting from removing the not structural materials (earth, clays, disaggregated stones etc.) on the top and around the sliding surface. Bricks in collapsing conditions (tilt – rotations), around the sliding surface, has been removed and placed nearby in order to a further reuse; this dismantling phase last until a masonry course with a proper arrangement has been found. Earth embankment behind the wall had been excavated for a depth of about 1m, in order to get a proper space for placing small stones as drainage, to avoid penetration of clay particles between brick joints with the consequential drop of friction, together with the decrease of water pressure against the wall in case of rain. Reconstruction of wall face and retro-filling with small stones proceed in same time, step by step. After two or tree layers of masonry, according to height of blocks, small stones has been placed until the last course was reached. In order to detect the new masonry and remark the restored part, a film of geotextile had been placed at the basement of the reconstructing zone. The lacking part of each zone has been rebuilt, as over described, using blocks without mortar, with the caution to pose the inferior side with a small opposite inclination respect to possible sliding movements and with a set of small stones forced into the joints to give proper equilibrium and pre-compression to each block. Bricks that have been used for reconstruction had been chosen in order to obtain a masonry texture similar to the adjacent.

3. Training experiences

3.1 Training of young engineers

Our team is organized in order to perform every phases of each mission with at least two members, especially in case of long term or important works.
The archaeological mission has been covered periods of about 9-10 weeks, with a sequence of three Units of Work. Before the start of every mission specific meeting, coordinated by the chief of the mission, has been performed in Pisa to establish the several phases of work and the main goals to achieve. The chief or his delegate will open the works, together with the first Unit of Work, to involve the first crucial activities as accordance with local authorities, logistics etc.

The minimum level for admitting members in a Unit of Work is the degree bachelor on civil engineering. The typical Unit of Work is composed by an expert member (with an experience of at least one mission) joined with another younger approaching the project for first time.

The expert member will show on site to the other one how to manage the particular building yard or which are the crucial steps of the restoration process, such as mortar colour tests or final beautification of joints and top, and the compiling of the final reports or other documents. The expert member is expected also to give useful skills on local market and materials or available tools and machines, and will introduce the new one to local traders and officers.

Formation of new engineers in each mission on this kind of work is particularly important to ensure a continuity in the team members and in the quality of the work, together with a appreciable didactical role as Practical Training on Field.

In the same time numerical and analytical models of the behaviour of the structures had been studied in order to find the physical parameters involved, the collapse surfaces and the safety of the restored masonry.

Proposed models, developed by members of the team and supported by laboratory tests on the used materials, represent an important step for the related scientific activities of the Department of Structural Engineering of the University of Pisa.

3.2 Organization of Construction phases:

The main problem connected to any restoration in foreign countries is the availability of particular materials requested for the work in the local market and, in case of positive response, where.

Moreover same tools, material or techniques may have different names, changing from area to area. Difficulties in communication may become consistent especially in case of dealing with sand truck or water tank drivers, due to the few percentage of English speakers between them. In the same time a sharp furnishing of material plays a crucial role in the plan of the work which schedule depends on the duration of the mission.

For all these reasons together with a limited opening timetable of building material shops and far location of the site, in this kind of organization, if not strictly planned every small unexpected event may cause a big loss of time.

The simple solution could be having someone whose duty is to organize the building yard and supply materials, together with more dialogue and cooperation between members of the engineering team and officers especially during the weeks before the mission, in order to have everything ready in the site since the first day of work.

3.3 Training of the manpower

Dealing with the manpower can be seen under two different, but strictly connected, aspects: anthropological sight and technical one.

All the Pakistani labours are just weight lifter, and most of them just can speak their native language. Indeed most of the specialized workers employed in the Sultanate of Oman for
similar restoration projects have progressively immigrated in nearby countries (United Arab Emirates, State of Qatar, Bahrain) after the so called “Omanization Laws”.
The first problem, then, is to teach them what to do and show them the work and on the same time trying to involve them to feel the importance of the work.
Usually they have a kind of hierarchical organization, that should be better to respect, speaking with the elected foremen and keeping him, in somehow, to support the engineer in the management of the labours.
Moreover just ordering someone to do something or not to do something else, is never a constructive way to proceed, particularly in this kind of work. For our personal experience, giving them selected and personal duties and responsibilities and also explaining them what they are doing and why, what is the aim of their job, what should be the schedule and the final results, played an essential role in the control of the site.
It has been very important making them to feel as vital members of a team and, if possible, trying to give them the instructions in their language in order to be sure to be understood and get their trust and respect.
It is easy to understand that having the same labours time after time, allow to reach good results, in a faster and easier way.
When we have had the same manpower team for two consecutive seasons, they already knew the work and, each one, his own duty. In this situation it had been possible to set up independent teams in different areas of the site; besides, most of them really felt the responsibility of their role in the team and were motivated to work at their best and to learn more, feeling the build yard also as a practical training in order to reach specialized knowledge.

References
