SUPPLÉMENT AUX ANNALES DU SERVICE DES ANTIQUITÉS DE L'ÉGYPTE

CAHIER N° 35

THE WORLD OF ANCIENT EGYPT
ESSAYS IN HONOR OF
AHMED ABD EL-QADER EL-SAWI

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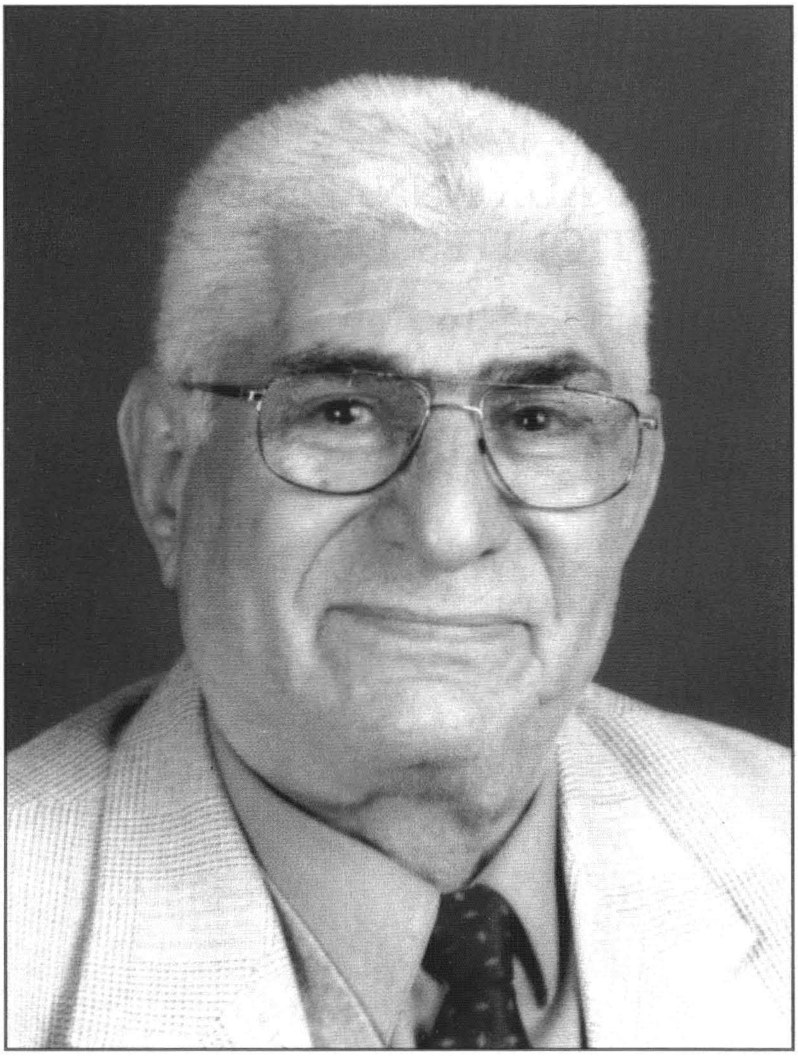
An offering scene from the mastaba of Ptah-hotep, Saqqara.



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IMPRIMERIE DU CONSEIL SUPRÊME DES ANTIQUITÉS

ENGINEERING STABILITY AND CONSERVATION OF THE SPHINX: DIAGNOSIS AND TREATMENT

Hany HELAL

Abstract

Since its existence for about five millennia, the Sphinx has suffered from different types of degradation and/or deterioration. Sources of such degradation can be classified as: nature, time, and man-made.

The present paper has two main parts. The first one concerns the actual current status of the Sphinx. After introducing the geological features, a zone risk map of the statue is presented. It also includes the structural discontinuities and their analysis, geotechnical parameters, probability of failure, the stress distribution concerning the stability of the head, and zoning of the critical part of the Sphinx.

The second part deals with the integrated proposal for the conservation of the Sphinx from the geotechnical engineering view.

1- Introduction

The Great Sphinx of Giza is a unique monument in ancient Egypt for its size, form, and even the sculptural techniques used in the Old Kingdom (2600 B.C.).

The Sphinx has been confronting serious situations of degradation and deterioration. Several phases of clearance and restoration have been carried out. The most important phases are[1]:

1st phase: 1400 B.C. (New Kingdom), Thutmose IV excavation and restoration

2nd phase: 500 B.C. (Saite Period), new excavation and restoration

3rd phase: 30 B.C. to 200 A. D, Roman excavation and restoration

4th phase: Baraize's 1926 restoration

The Egyptian Antiquities Organization started the 5th phase in 1955 which lasted until 1988. It is worth mentioning that none of these restorations have considered the stability of the Sphinx, except Baraize who was worried about the solidity of the neck. All the proposals that have been made to stabilize and preserve the Sphinx did not include necessarily carrying out scientific, diagnostic work on site. Little effort has been made to give proper attention to all possible causes of deterioration. One important parameter was always missing: the restoration concept (the conceptual restoration).

It has been noticed that all restorations carried out until now were based on spontaneous reactions and interventions. What had been done was only to restore some parts of the statue that were obviously deteriorated, meanwhile the origin and causes of this deterioration were not well identified. It came to the point that actually most of the present work carried out is restoration of the previous restoration, and the statue is still suffering.

In order to start a complete action-oriented plan of restoration, it should be organized within the framework of a well identified conceptual plan. Restoration for the archaeologists, even in antiquity, was mainly based upon concepts relative to:

1 Z. Hawass, 'History of the Sphinx Conservation', *The First International Symposium on the Great Sphinx* (Cairo, 1992), 165-214.

- the shape of the statue
- the anatomical features of the statue
- the consideration of previous restorations

Another important parameter that should be taken into consideration is the visual essence of the statue. The art historian E. Houssman stated that 'the Great Sphinx is a ruin and it should be kept as it is'. This is a very important fact, and what is needed for the engineer to start an integrated restoration plan is the decision for a restoration concept.

These points are fundamental, although the problems of the stability of the statue (the mother rock as well as the masonry) must be definitely solved before in order to avoid what is happening today: the premature degradation of the last restorations.

From the engineering point of view, the Great Sphinx is a structure made of natural material subjected to the influence of internal and external factors. Therefore, the structure stability of the Sphinx is essentially based on the qualitative and quantitative evaluation of the behaviour of this natural structure under the action of various environmental parameters.

The present work aims at presenting the engineering methodology that could be used in such cases together with a systematic view of degradation parameters. In addition, a preliminary zone risk map of the Sphinx and a two-dimensional modeling of stress distribution around the neck will be presented.

2. The Engineering Approach

As stated before, the main objective of the engineering analysis is to ensure the stability of the structure under different environmental conditions. It will be achieved through the following stages:

-evaluation of the mother rock's current status from an archaeological point of view

-qualitative and quantitative estimations of relevant factors affecting the body and the surface of the statue

-integrated modeling of the statue environment

-remedial policies, monitoring, and control

2. 1. Adopted Methodology

Experience gained in the field of geotechnical engineering applied to civil and mining projects has been adopted so that it can be used in the preservation of monuments.[2] The investigative procedure is outlined in figure 1 and could be divided into a succession of main stages:

A. Carry out exploratory work and collect sufficient data on the site; it is a multidisciplinary investigation. The data collecting concerns:

- The surrounding area (topographic, geological and geotechnical survey, climatic conditions and human activities)
- The Sphinx body (historical and architectural documentation, structural elements and architectural analysis, accurate geological and geotechnical survey, rock characterization of the body and the construction material features .... etc.)

2 J. P. Piguet, H. Helal, and H. Imam, 'Les Phénomènes Géotechniques des Sites et Monuments de l'Antiquités Égyptiènnes', *International Symposium on the Engineering Geology of Ancient Work, Monuments and Historical Sites* (Athens, 1988); Helal, T. Abdallah, and H. Baroudi, 'Behaviour of Ancient Cavities in Discontinuous Media: The Baboon Tomb Case Study, Saqqara, Egypt', *International Symposium on Rock Mechanics* (Swaziland, 1990).

B. Analyze the data and define the interaction between the different phenomena.

C. Establish the most probable hypothesis of behaviour. These later steps, B and C, require the most experience. It may be helpful to use the recently developing science, the 'dynamic of systems', to find out the consequences on the whole environment of the monument if a confined change of this environment occurs.

D. Modeling the structure and anticipate the future behaviour of the monument; this is necessary to check the hypothesis of behaviour. Modeling categories include: physical, analytical, and numerical.[3]

E. Select parameters to be observed, calculate their anticipated values, and measure them. Monitoring is usually planned so as to:

- record the natural values of geotechnical parameters and structure displacement and to study their variation
- ensure safety during restoration operations
- check the validity of the assumptions, conceptual models, and values of soil or rock mass properties used in calculations
- control the implementation of monument treatments and remedial policies

F. Modify the model to suit the actual conditions (according to the monitoring measurements) to forecast the future probable phenomena and the validity hypothesis.

G. Determine the most suitable engineering solution using modern tools of geotechnical engineering.

H. Carry out monitoring to check the efficiency of restoration.

2. 2. Sources of Degradation

The sources of degradation for historical monuments have been recorded and classified by Verdel and Helal in 1992.[4] They can be summarized hereafter with reference to the Sphinx as follows:

-The action of time

-The action of nature

-The action of man

The Action of Time

It represents the direct action of gravity. The equilibrium between the acting gravity loading and inherent strength of the rock mass of the Sphinx is the consequence of the action of time. No total ruin is observed within the Sphinx; only local instabilities have been recorded.

The Action of Nature

It deals with several factors. These are:

-Geology, i.e. the type of rock and discontinuities (structural geology)

-Solar radiation, which involves temperature variations in space and time

-Humidity, responsible for the alteration of the rock and of the salt crystallization. It may be due to underground water, relative humidity of the air, ...etc.

-Rain is also a source of humidity as well as a source of erosion. Moreover, carrying dissolved gas from the atmospheric pollution, it causes chemical alteration.

3 Helal, Abdallah, Imam, T. Verdel, Piguet, 'Numerical Modeling as a Tool in Identifying Geotechnical Phenomena', *The Third Mining, Petroleum and Metallurgical Conference* (Cairo, 1992).

4 Verdel and Helal, 'Environmental Impacts and Degradation of Archaeological Sites and Monuments in Egypt', *The Third Arab International Conference on Material Science: Degradation and Stabilization of Material* (Alexandria, Sept. 1992).

-Wind, carrying sand or no sand or dust, is the main factor of erosion and may be a source of vibration.

-Natural disasters, mainly earthquakes, but also very heavy rains and floods

-Bioactivity or biodegradation, includes the damage caused by microscopic organisms (bacteria, microscopic seaweed, mushrooms, ...etc.) as well as that involving insects, birds, or mammals.

The Action of Man

It can be divided into two parts:

1. Direct causes:
   - Wars that took place at Giza Plateau
   - Voluntary mutilations of the face of the Sphinx in the past and the absence of cultural awareness nowadays
   - Poor maintenance
   - Improper restoration and the use of unsuitable material for restoration

   The last two points may be due to the limited technical resources and to unadapted management.

2. Indirect causes:
   - Atmospheric pollution of industrial development (dust, smoke, gas)
   - Pollution due to urban development
   - A rise in the water table because of liquid wastes
   - An increase of the level of vibrations due to traffic or due to the construction of buildings (microseism)
   - An increase in pollution due to dumps near the Sphinx

2. 3. Integration of the sources of degradation

It is clear that the factors responsible for the degradation of the Sphinx interact together and increase the effect of one upon the other; therefore, considering them an integrated system is indispensable to the engineering analysis and evaluation.

For example, the underground water is directly involved in the decay of the stone because it wets the blocks and increases the erosive effect of the wind by decreasing rock properties, and it is the means of transportation of salts into the discontinuities which, when crystallizing, increase the effect of these cracks. At the same time, the discontinuities have a role in the rise of underground water up to the body of the Sphinx. Thus, the discontinuities increase the role of the underground water which increases, through salt crystallization, the effect of the discontinuities. The utility of such systematic approach is quadruple:

1. It gives a global and comprehensive view of all the factors of degradation of the Sphinx, and, above all, it gives the interrelations between one another. It helps to determine which factor is a real cause and which is just an intermediate one.
2. With computer assistance, it permits the evaluation of the consequences of a small modification on one environmental factor for the monument and its environment.
3. It defines the importance of each factor and its priority of intervention in a plan of restoration of the Sphinx.
4. It will help determine the necessary experiments to assess qualitatively the relationships between different factors.

Figure 2 gives an example of the interaction between different factors of degradation focused on three categories:

-the local instabilities of the mother rock

-the erosion of the mother rock

-the decay and instabilities of the masonry

2. 4. Zone Risk Map of the Sphinx

Since all the factors of degradation of the Sphinx interact, it is necessary to deal with them as an integrated system. Thus, the exact situation can be shown through an accurate survey of the site. The recorded observations and their analysis should be considered when producing the Zone Risk Map. Once the level of risk is determined, the necessary interventions can be easily adopted.

In the case of the Sphinx, the Zone Risk Map should include:

A. Geological conditions: the Sphinx body is formed from three limestone layers. These correspond to the principle parts of the statue: a hard layer at the base, a softer marl layer from which the body was cut, and another hard layer in which the neck and the head were sculpted.

B. Rock discontinuities and cracks: a structural survey has been conducted on the Sphinx.

The discontinuities are almost invisible on the body of the Sphinx, as its lower half is covered with masonry; in the upper part, the open fractures are filled with mortar. Thus, our measurements have been done mainly on the walls surrounding the statue.

Fifty-three discontinuities have been measured and represented on the structural map of the Sphinx (Fig. 3). The Sphinx appears as an assembly of about 14 main blocks. The general stability of the Sphinx is, therefore, to study the structural stability of these blocks. Analysis of measured discontinuities using stereographic projection shows that there are two main families of discontinuities:

1. Primary sets: N 38° E 8°, N 20° W 90°

2. A secondary set: N 40° W 76°

C. Areas where the erosion is the most effective

D. Masonry problems

E. Zones of high probability of failure, either due to the presence of joints or due to flaking and exfoliation

F. Some additional information, like the restored zones (Baraize, 1926)

A preliminary Zone Risk Map is illustrated in figure 4. The examination of the obtained Zone Risk Map may lead to the following remarks:

- The pattern of wind erosion is visible all around the body of the Sphinx, but erosion is especially apparent on its chest. It may be due to the special shape caused by the chin, the chest, and the forearms that may involve some particular aerodynamic conditions.
- The cracks: the front elevation shows six cracks in the head which have to be carefully monitored. Two of them are particularly worrying.
- The crack under the chin, which, if it evolves, will cause serious problems to the head.
- The crack that separates the ear to the edge on the southern part of the headdress increases the probability of failure of the lower part of the southern side of the headdress.
- Probability of failure: a few zones of probable failure are located in the high, southern part of the body. They are formed by an assembly of several small blocks separated by a net of cracks or discontinuous planes.

- These discontinuities: they are mainly sub-vertical or vertical
- Masonry damages: the phenomena of explosion of blocks that are located at the convex and overhanging places on the northern side: the extremities of the forearms and the base of the tail.

3. Stress Distribution around the neck

The neck of the Sphinx, especially its back, is eroded by the wind in such a way that this area requires particular attention. The following study is the first stage of a two-dimensional attempt at calculating the stress distribution around the neck. The aim of the first study is to investigate:

- the present stress distribution in the neck area
- the stress variation since the Sphinx was first cut

Modeling has been done using stress analysis code on distinct element method; the geometry of the model is given on figure 5. Plane stress conditions were assumed, and the blocks are considered as continuous media. Rock characteristics determined on intact rock samples are used. The real characteristics which take into consideration fracture and joint effects are estimated using standard procedure (such as Bieniawski rock mass classification), and joint effects are estimated using standard procedure (such as Bieniawski rock mass classification).

Two models were realized: one representing the Sphinx as it might have been originally, with its beard and nape not eroded; and the other representing the Sphinx as it is nowadays, without beard or nape. Figure 6 shows the principal stress distribution with and without the beard.

A vertical stress concentration spreads from the chin to the chest due to the overhanging of the face (max. value: compression 0.38 Mpa). A concentration of horizontal stresses (max. value: compression 0.12 MPa) is located at the top of the back.

Figure 7 shows the evaluation of stresses under the chin of the Sphinx. Stage one corresponds to the state before excavating the Sphinx. Stage two corresponds to the creation of the Sphinx and stage three to the loss of the beard. The corresponding factors of safety are 6.8 for the Sphinx with beard and nape and 2.9 for the Sphinx without beard or nape. There is a decrease in the safety factor of 57% due to the stresses induced by the elimination of the beard, approaching the safety factor of 3.

However, it should be kept in mind that regarding the shape of the statue and the net of measured discontinuities it is obvious that a two-dimensional model is too limited and cannot give the true behaviour of the structure. A three-dimensional model is recommended (e.g. TRIDUC).

4. Conclusion

Conservation of the Great Sphinx is a tedious, long-term, multidisciplinary, action-oriented project. It requires an integrated system based on the interaction between the different sources of degradation. Once the restoration concept is established by Egyptologists, the engineering approach presented here could be adopted as a global methodology towards a master plan of conservation.

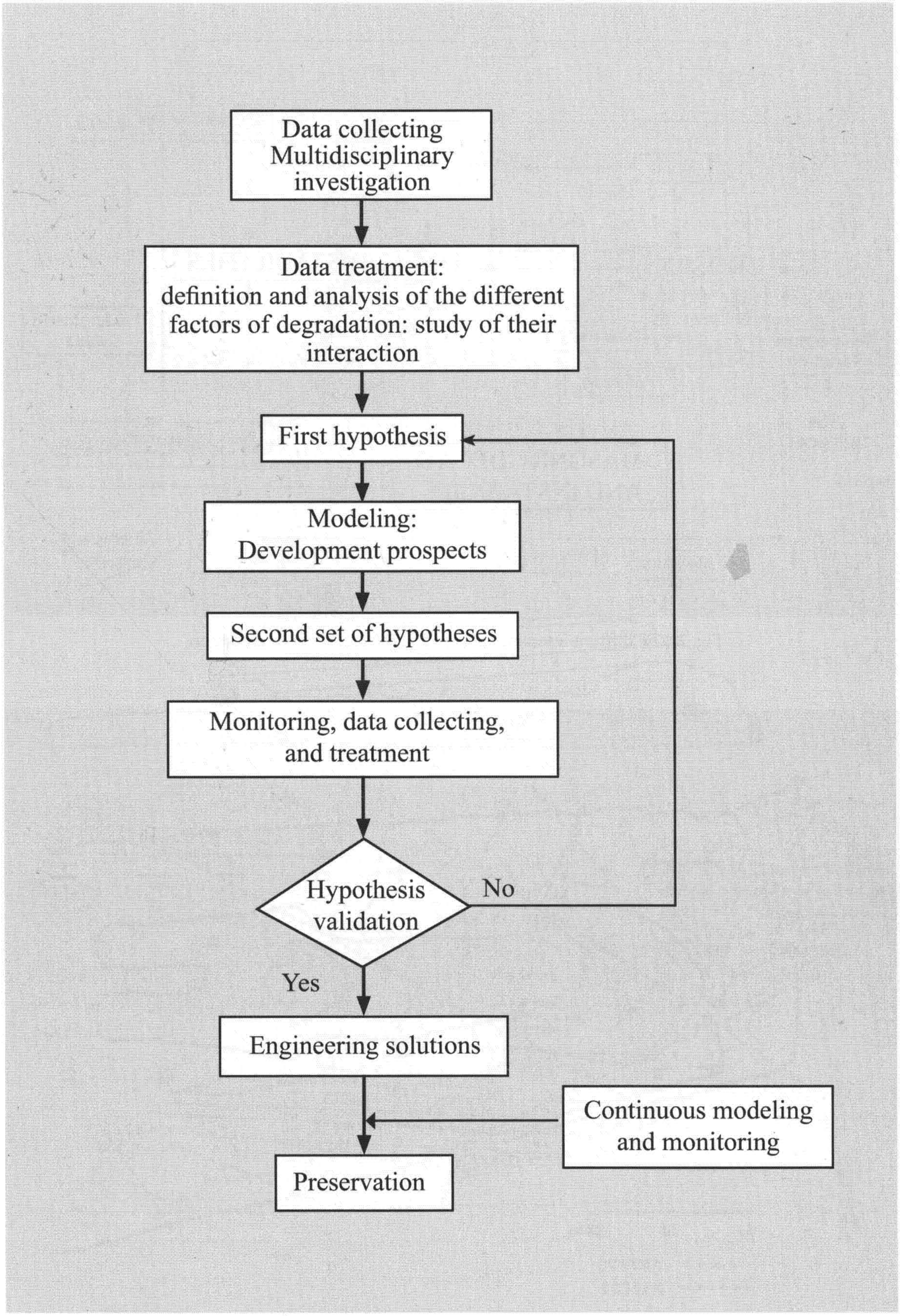


Fig. 1. Adopted Methodology.

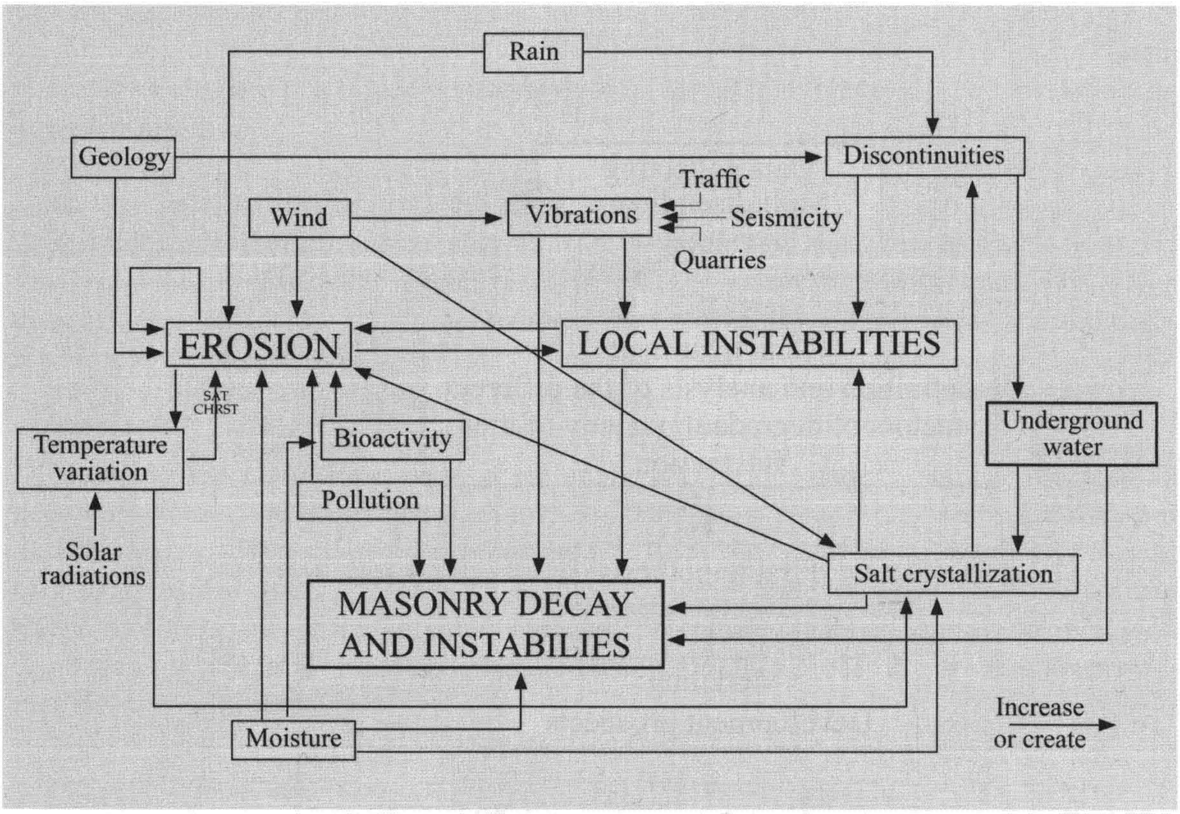


Fig. 2. The diffrent interactions between the factors of degradation.

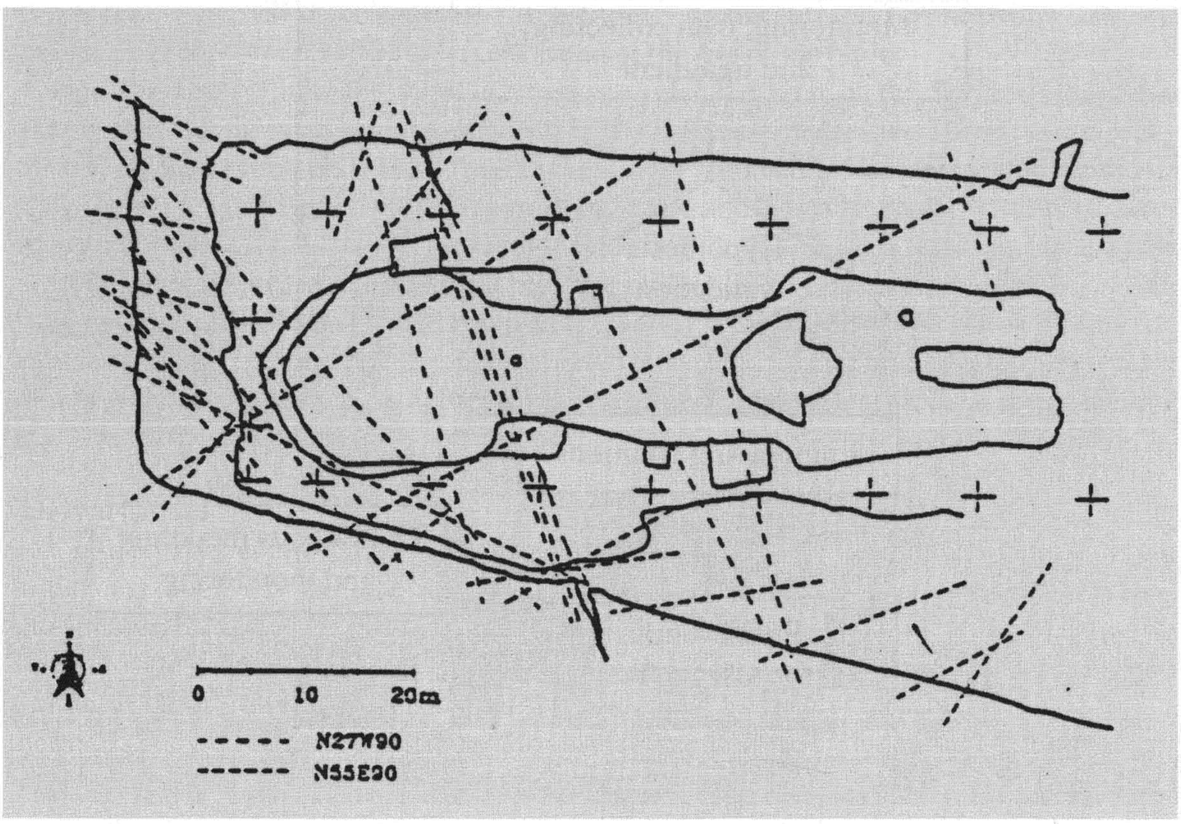


Fig. 3. Structural map of the Sphinx.

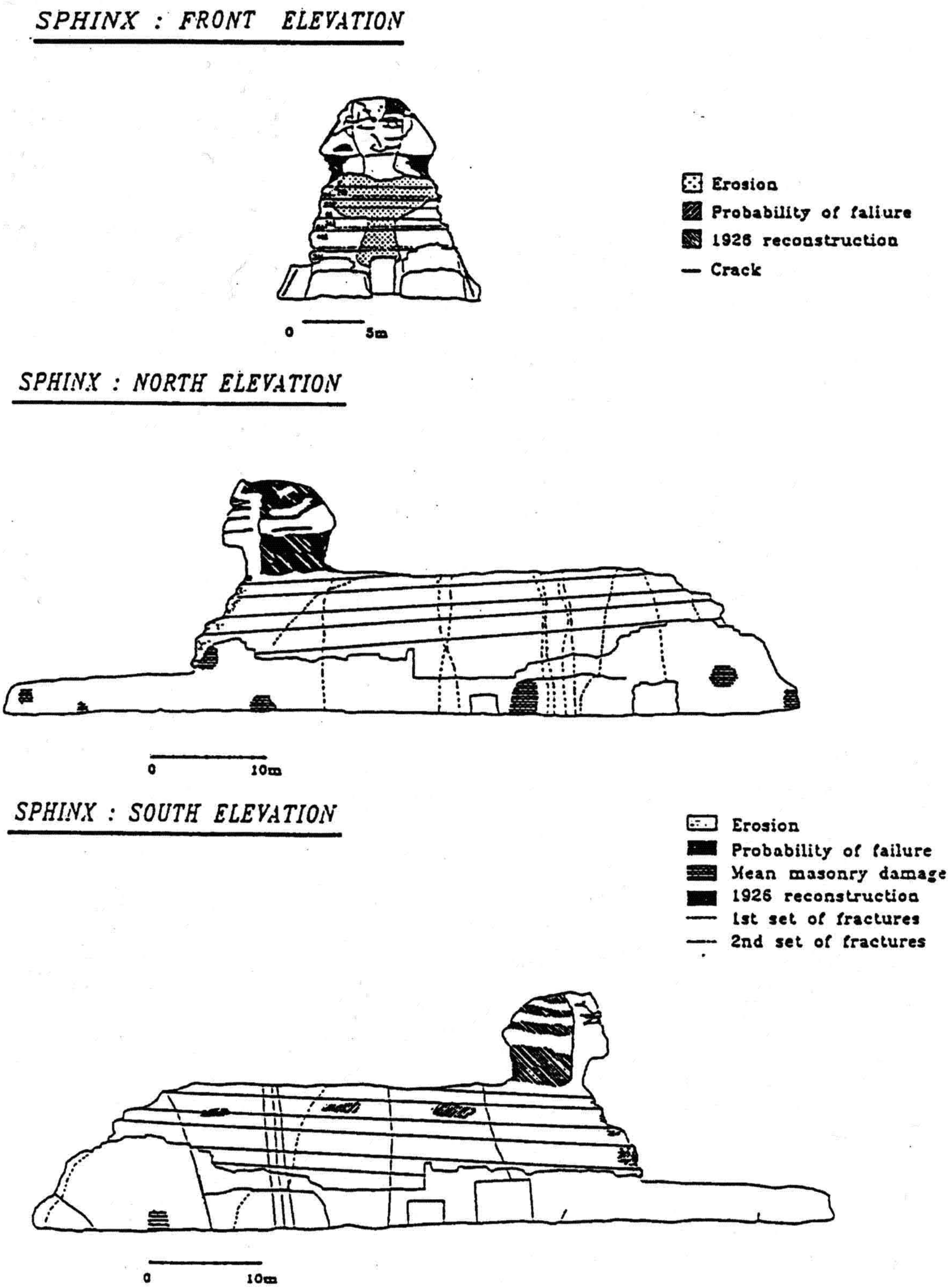


Fig. 4. Preliminary zone risk map of the Sphinx.

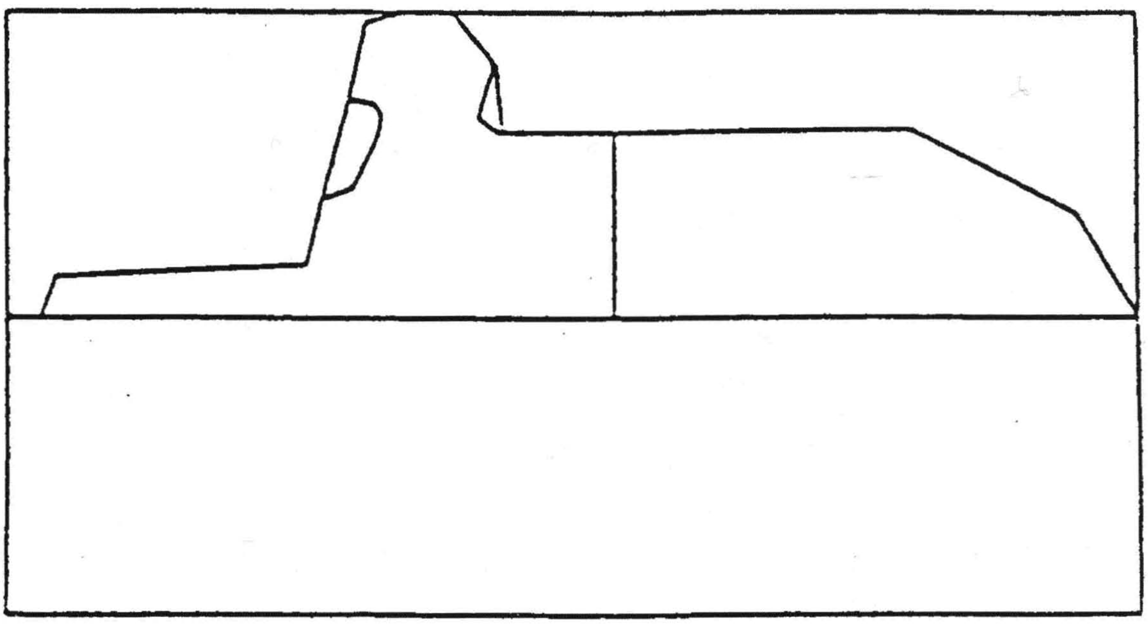
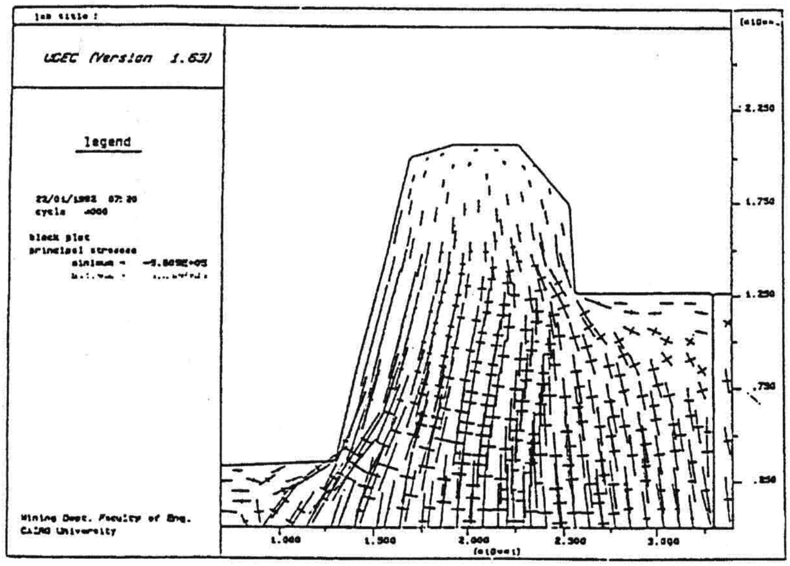
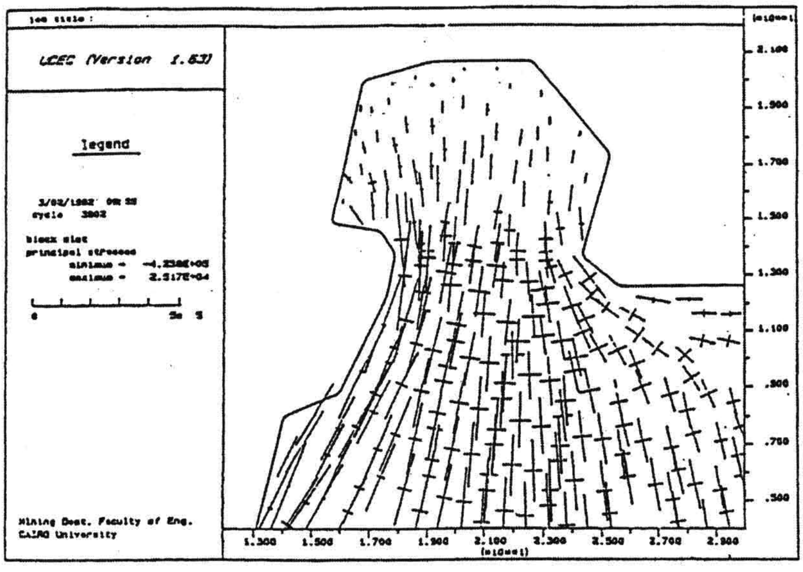


Fig. 5. Used model of the Sphinx.



a. with beard



b. without bread

Fig. 6. Stress distribution in the Sphinx neck.

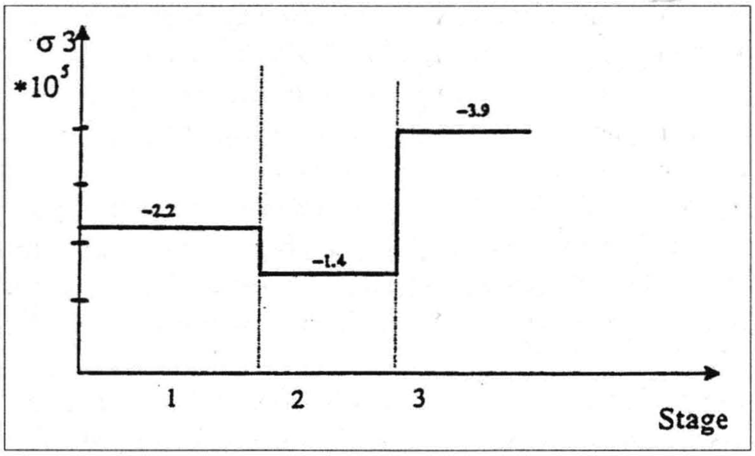


Fig. 7. Evaluation of the stresses under the chin of the Sphinx.

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