United Nations
Educational, Scientific and
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APSARA

A Charter for Angkor

Guidelines for Safeguarding the World Heritage Site of Angkor

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APSARA
Authority for the Protection and
Management of Angkor and
the Region of Siem Reap

A Charter for Angkor

Guidelines for Safeguarding the World Heritage Site of Angkor

Siem Reap, Cambodia
5 December 2012

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Foreword

In recognition of the outstanding universal value of the Angkor World Heritage site and in order to address the challenges of safeguarding its precious but fragile attributes, this document was prepared to assist technicians working in the field to plan and implement conservation interventions using a shared philosophy, while respecting diversity and specificity with regard to each situation.

For the past 20 years, experts have been meeting and discussing the technical issues involved in cultural heritage safeguarding at Angkor. This document aims at outlining the consensus of opinion on key questions. These guidelines will assist heritage professionals in planning and implementing appropriate conservation and restoration operations.

The document is divided into two parts. The first, under the heading "Principles," outlines some of the basic tenets of conservation that were already agreed upon at the international level and can be found in various charters. In particular, we refer to the recommendations of ISCARSAH, the International Scientific Committee on the Analysis and Restoration of Structures of Architectural Heritage, a technical committee of the International Council on Monuments and Sites (ICOMOS).

The second part, "Guidelines," provides technical recommendations and is divided into many subchapters which, in summation of extensive debates, broach such problems as the acquisition of data, diagnosis and safety evaluation, the identification of materials used during the construction of the temples in the Angkor region and, finally, the building techniques used. The causes of the decay and subsequent alterations to the temples are subsequently dealt with, as are leading methods of research and evaluation, as well as systems to record and archive data.

The recommended criteria and techniques for the conservation of the Khmer monuments at Angkor are detailed. The concluding chapter of the document deals with issues related to the protection of the monuments and the establishing of a risk map.

History of the Angkor Site

The sprawling archaeological complex of Angkor and adjacent sites – Roluos and Banteay Srei – are found in Cambodia, about 20 km north of the Tonle Sap (or Great Lake), roughly 300 km to the north by road from Phnom Penh. Human settlements in this area date back for millennia. The first Hindu monuments (Prasat Ak Yum, Trapeang Phong) possibly appeared in this region by the early 7th century AD. A few years later, one king located his capital Hariharâlaya around his palace, Prei Monti, and built an initial temple, Bakong. Jayavarman II seized this same capital in the late 7th century before being consecrated as “king of kings,” cakravartin, at Phnom Kulen in 802, where he also died circa 835. His son Jayavarman III succeeded him, although the date of his death remains elusive.

Indravarman I, one of his relatives, ascended the supreme throne in 877. He “modernised” Hariharâlaya, completely restoring Bakong, among other things putting a sandstone facing the on the whole temple, reactivating Preah Ko temple as a sanctuary dedicated to former kings and establishing to the north the first major reservoir or baray, 3800 m in length by 800 m in width.

Yaçovarman I, his son, was the founder of the city of Angkor, Yaçodharapura, a name apparently used for centuries. This city or at least the “State temple,” was relocated several times. The city seemed to have centred around a hill, Phnom Bakheng, on top of which the king had a huge pyramidal temple erected. Simultaneously, he developed Yaçodharatatāka or the Eastern Baray, the first of the two largest Angkor barays (measuring 7.5 km by 1.8), to the south of which he constructed large āçrama or hermitages devoted to each of the main religions of his empire.

This king was then replaced in succession by two of his sons, Harshavarman I (910–circa 920) and Īçānavarman II (circa 920–circa 928). The first erected Baksei Chamkrong, a small pyramid dedicated to the memory of his parents. During his reign Prasat Kravan was also built.

The following king, Jayavarman IV, was reigning in Koh Ker when he seized the supreme throne, probably by force. Consecrated in 928, he remained in his capital where he or his ministers had some 40 temples built, including the prang, the highest Khmer pyramid. He died in 940, although the heir he designated was quickly replaced by one of his brothers, Harshavarman II, who only reigned for a few years.

This was in 944, when his first cousin, Rājendravarman, ascended to the supreme throne after returning to Angkor. However, he set up his capital to the south of the Eastern Baray, around his State temple, Pre Rup, consecrated in 962. He had previously built the Eastern Mebon at the centre of the baray. He died in 968, most likely assassinated. The same year marked the consecration of the statues of Banteay Srei, a temple erected by the king's guru, Yajñavarāha.

Jayavarman V succeeded his father Rājendravarman, and seemingly enjoyed a peaceful reign. Before his death in 1000, he had Ta Keo temple and his palace built to the west of the Great Baray.

The ensuing period remains somewhat unclear: Jayavarman V's first successor was short-lived, as he died in 1002 or just before. Two men then had themselves consecrated "king of kings" in the year 1002, both of unknown lineage. Jayavīravarman settled in Angkor and continued the construction of Ta Keo, whilst Sūryavarman I commenced his reign in the region of Battambang. A decade-long war ensued and a triumphant Sūryavarman I settled in Angkor, but erected solid ramparts around his royal palace estate, later to be known as Angkor Thom. In addition to his palace, he located the Phimeanakas, a relatively modest State temple, within its precinct. He reigned until circa 1050, and saw to construction of the immense Western Baray (8 km long by 2.2 wide) and most likely started building the Baphuon, although he died before completing it.

He was succeeded by his son, Udayādityavarman I. The latter continued erection of the Baphuon and put in the Western Mebon at the centre of the baray. Nevertheless, he had to contend with violent upheavals. After his death in circa 1066, his brother Harshavarman III succeeded him on a potentially weakened throne. The latter had to continue fighting the upheavals, with no great success.

He died in 1080, leaving the throne to Jayavarman VI, most likely his victor. Only a few details have emerged on the lineage of this king, simply that he originated from Mahīdharapura, a site which has yet to be located. He reigned until 1107, but he is not known for having built any major monuments. The temple of Pimay, now in Thailand, was built during his reign.

He was succeeded by his older brother, Dharaṇīndravarman I, but was soon eliminated by one of his grandnephews, Sūryavarman II, in 1113. He is remembered in history as the builder of Angkor Wat, the great masterpiece of Khmer art. Yet, he dedicated most of his time to waging war, in particular against the Vietnamese. He died circa 1145.

Another period of uncertainty commenced. Little is known of Yaçovarman II, the king who assumed the supreme throne and died in 1165, during an ambush led by his successor Tribhuvanādityavarman. The latter’s achievements and reign also remain vague.

In 1177, a Cham king with the support of a Khmer army conquered Angkor. It is commonly argued that he came with the intent of placing one of his Khmer friends on the throne. It was then that the future King Jayavarman VII was waging war against Cham (and Khmer) enemies and attempting to take control of the Khmer land, likely already in a disintegrated state. He only managed to accede to the throne in 1182 without having established complete peace. He was a great organiser, and to him has been attributed such things as the revival of hospitals. A devout Buddhist but with a tolerant approach, he was a tireless builder in Angkor and the provinces, although it is unlikely that he could have built all the buildings that have been associated with his name. In Angkor these include the temple and city of Ta Prohm, the temple and city of Preah Khan and the accompanying baray, the Neak Pean, the city of Angkor Thom and the Bayon and its Royal Palace.

He died circa 1220, and the little-known Indravarman II succeeded him. It is most likely that as he was also a devout Buddhist, he continued during his long reign the construction commenced by Jayavarman VII, although the two men do not seem to be of the same lineage.

He was succeeded in 1270 by Jayavarman VIII who seemed to have dedicated his time to erasing any traces of the religion practiced by his immediate forebears by systematically destroying all of the Buddha figures that were abundantly disseminated throughout Angkor. Simultaneously, he saw to the restoration of former Hindu monuments, in particular Angkor Wat and the Baphuon. It was toward the end of his reign that Zhou Dagan, a Chinese diplomat, made a glowing record of his observations of Cambodian customs and wealth at the time. Jayavarman VII abdicated in 1298 to one of his sons-in-law, Śrīndravarman, a more open-minded man who allowed both main religions to flourish.

From this date onwards our knowledge of Angkor is sparse. We know the names of two kings, Śrīndrajayavarman and Jayavarman Parameśvara. But the political history of Angkor from the late 13th century onward is largely unknown. Nevertheless, monuments built during this period such as Preah Pithu and Preah Palilay can be admired. Angkor was thus reduced to a small peaceful kingdom, yet still very much alive, with some relevant events in the late 16th century.

GUIDELINES FOR SAFEGUARDING THE WORLD HERITAGE SITE OF ANGKOR

Part 1: Principles

- The conservation, reinforcement and restoration of architectural heritage require a multi-disciplinary approach.

- The value and authenticity of architectural heritage cannot be assessed with set criteria as each culture is different and has to be respected as such, and requires that its physical heritage be considered within the cultural context it belongs to.

- The peculiarity of heritage structures, with their complex histories, requires the organisation of studies and analyses following steps that are similar to those used in medicine. Anamnesis, diagnosis, therapy and controls find their respective corollaries in the current condition survey, identification of the causes of damage and decay, choice of measures to remedy these issues and monitoring what has been achieved through the interventions. In order to be cost-effective and ensure minimum negative impact on architectural heritage, it is often appropriate to repeat all of these steps in an iterative process.

- A full understanding of the structural behaviour and characteristics of the constituent materials is essential for any conservation and restoration project. Research should be carried out on the original and earlier states of the structures, on the building techniques and construction methods used, on subsequent changes, on the various phenomena that impacted the structure, and finally, on its present state.

- Before making any decision on structural intervention it is indispensable to first determine the causes of damage and decay, and then to assess the present level of structural safety.

- Implementing an adequate maintenance programme can limit or postpone the need for subsequent intervention.

- No action should be undertaken without demonstrating that it is indispensable.

- The design of any intervention should be based on a full understanding of the kinds of action, forces, accelerations, deformations or agents that have caused the damage or decay and of those that will act in the future.

- The choice between “traditional” and “innovative” techniques should be determined on a case-by-case basis with preference given to those that are least invasive and most compatible with heritage values and consistent with the need for safety and durability, as well as the availability of means for their maintenance.

- At times, the difficulty of evaluating both the safety level and the hoped-for benefits of interventions may suggest an “observational” method or incremental approach beginning with a minimum level of intervention, with the possible adoption of subsequent corrective measures.

- The characteristics of any new materials used in restoration work and their compatibility with existing materials should be fully established. This must include their long-term effects, so that undesirable side effects are avoided.

- The distinguishing features of the structure and its environment that derive from its original form and any significant subsequent changes should not be altered.

- Each intervention should, as far as possible, respect the original concept, construction techniques and historical value of the structure and the historical record that it provides.

- Repairing is preferable to replacing.

- Imperfections and alterations that have become part of the history of the structure should be maintained, provided that they do not compromise safety requirements.

- Dismantling and reassembly should only be undertaken when required by the nature of the materials and structure and/or when conservation by other means is more damaging.

- Measures that are impossible to control during execution and the effectiveness of which has not been verified should not be allowed. Any proposal for intervention must be accompanied by a monitoring and control programme to be carried out as extensively as possible while work is in progress.

- All conservation control and monitoring activities should be documented and retained as part of the history of the structure.

- Preventive archaeological research or archaeological surveying must be done upstream from any conservation work on the Angkor site. A methodical trench diagnosis and survey excavations will enable an assessment to be made of the impact of the intervention on the archaeological and monument heritage, providing a basis for any necessary safeguarding, investigation and documentation work.

Part 2: Guidelines

I. General Considerations

These guidelines should lead to a better upstream understanding and consequently to improved design and planning of interventions for the conservation and safeguarding of the Angkor temples. However, they are in no way intended to replace thorough scientific and cultural analysis and research, which these recommendations are meant to dovetail.

The general structural design of the temples of Angkor is simple and intelligent. Yet, any conservation and restoration project has complex issues to face. The interaction between major material decay and/or structural damage – the consequences of various factors of decay and deterioration – has to be taken into account, as will be developed further on.

Serious instances of deformation and partial collapse have occurred and frequently pose problems not only for the conservation and strengthening of the monuments and decors, but also for partial dismantling and rebuilding operations.

The challenge is to find a correct balance between safety and durability without causing any loss of the significance and authenticity of the monument and the traces of the history found on it.

The constituent materials are subject to natural alteration and decay. Conservation of such materials and the carved surfaces, characteristic of the temples of the Angkor region, is as important as structural conservation.

It is important to understand the status of the monument not only in the fields of statics and preservation, but also its significance. A monument can have different meanings depending on the stakeholders, and this can have an impact on the technical approach chosen to preserve it.

The relationship between the monuments of Angkor and the environment is a complex one. The fact that tree growth has encroached on many of the temples during their years of neglect is now considered as part of the natural and cultural heritage of the site. The techniques and technologies to be used must therefore fit within the framework of a general cultural approach. The problem is compounded by the fact that forest and vegetation cover can have a severely detrimental effect on a structure. However, it should also be noted that the clearing of forest cover may also be damaging, as this has an immediate and drastic effect on the microclimate and groundwater level. This underlines the need for a thorough ecological and arboreal survey at Angkor.

The thriving natural environment is a characteristic of the site and must be taken into account when selecting not only the techniques and technologies to be implemented, but also the overall cultural approach. Vegetation is an undeniable cause of damage and decay, but the venerable trees on and around the monuments are an exceptional and unique part of the cultural value of the site and as such should be preserved for as long as possible, even if a compromise may have to be found with the integrity of a structure, which might need to be strengthened as a consequence of the action of nature.

However, it should be remembered that these trees have a life cycle and will inevitably die and fall, thus presenting a risk sooner or later to their host temple. Therefore, trees must be constantly monitored by experts. They should be preserved for as long as possible, if necessary by implementing special measures, but should be removed when there is an imminent risk of falling. The compiling of a comprehensive risk map in tandem with a plan of monitoring and maintenance by forestry and conservation experts is an immediate priority.

The philosophy for conservation and restoration has not been linear in time, but rather ever-changing, due to experience acquired and progress made by the rapidly increasing number of related fields, along with more comprehensive thinking on cultural aspects. Some new fields arise out of necessity, and may not be directly related to restoration and conservation activities.

The problems involved in large interventions are nothing new. At one time, reinforced concrete was used extensively for restoration work. Now things are different. When working with this type of situation, a coherent project compatible with the philosophy formerly implemented has to be formulated.

The purpose of these recommendations is to contribute to greater awareness and understanding of the various problems and possible solutions. They are not meant to be strict rules when selecting the intervention criteria, as such criteria depend on each specific context and environment. Conserving the structures and strengthening them as least invasively as possible should be the guiding principle. Sometimes a different approach, such as dismantling and reassembly and/or simply retaining the romantic character of archaeological ruins, may be just as valid.

Conservation must always be recognised as an interdisciplinary process. Experts of all conservation fields play an equal role in the planning process and in implementing and monitoring the intervention.

With regard to reversibility, we have to distinguish between structural interventions, on the one hand, and the conservation of materials, on the other hand. In the first case the approach is usually one that will work, whereas in the second, it is almost always impossible to achieve complete conservation of materials. Thus, the compatibility and effectiveness of materials should be considered and all methods and materials should be extensively tested in the laboratory and on site before being applied in a conservation operation.

The reversibility of an intervention, although a determining factor, must not be considered as a hard and fast rule. Firstly, because intervention reversibility excludes many compatible and commonly used materials (lime-based injection mortar to name but one) and secondly because most materials that are considered reversible in laboratory conditions are almost never fully reversible on site (for instance organic resins).

The conservator must take full responsibility for his choices and therefore must be able to scientifically prove that his choices are correct. All steps in the conservation material selection are to be documented.

An important requirement of the conservation materials to be used is their compatibility – chemical, physical and aesthetic – with the original, especially under the extreme tropical climatic conditions prevailing at Angkor.

In recent decades, a significant number of innovative materials, techniques and technologies have come to the fore. Their effectiveness and benefits have recently been critically assessed both from the technical and cultural points of view. It is now accepted that in some situations they contribute to the safeguarding of monuments better than traditional techniques. Thus, all methods and materials, both traditional and modern, should be considered and scientifically (and culturally) appraised before being included in a conservation intervention. Given the failure of some modern techniques and materials in the recent past, it is particularly important to assess their positive and negative impacts.

This Charter for Angkor differs from other similar documents in that it refers to particular structural/architectural typologies and to specific environmental conditions.

Therefore, the general principles have to be redefined with sufficient flexibility in relation to the particular issues faced on the Angkor site. Correct conservation is achieved through a careful balance between the general and particular, the universal and specific, between what is common to all monuments and what is specific to the monuments of Angkor and their environment.

Interventions must be guided by an overarching respect for the authenticity of the monuments. With regard to the Angkor monuments, respect for authenticity covers many different things. The authenticity of the form and geometry, the authenticity of the materials, the authenticity of the structure and its static behaviour, the authenticity of the environment of the monument and the authenticity of its function and/or use should be respected.

Sometimes, these different aspects of authenticity seem contradictory. Conservation of the environment of the monument and therefore of the trees that have grown on the temples and which may actually threaten the structure is an example. Another instance is that of materials that have been lost due to weathering or collapse. This process is part of the history of the monument, but at the same time may it may give rise to serious problems with regard to the geometry, the original shape of the structure and therefore its cultural authenticity.

Conservation and restoration should, as much as possible, respect all components of the overall concept of authenticity, but in case of contradiction or incompatibility among the different specific aspects mentioned above, it is necessary to strike a balance on the basis of thorough analytical thinking and by studying the pros and cons of each possible approach.

The final approach should favour the aspects which are the most significant for that specific monument in the general context of the site.

That means that different approaches may be selected for different monuments with similar problems. The important thing is to respect the spirit rather than the letter of the general principles, basing one's choices on rational thinking guided by universal, consistent and ethical behaviours.

II. Impacts on the Structures

There are different kinds of actions that influence or impact on materials and structural behaviour. These can be divided into different groups that are described as follows:

a). Direct static impacts:

These impacts are represented by forces arising from the sheer weight of the structures, the loads applied, such as human presence, etc. Usually, the weight of the structure is the greatest among the loads in this category.

b). Indirect static impacts:

Such impacts are not represented by immediate forces, as in the previous category, but by deformations sustained by the structure.

The deformations can be either “internal,” such as the intrinsic characteristics of the materials (temperature deformations, creep and viscous deformations, etc.) or “external,” such as movements having an impact on the structure through soil movements.

If these deformations cannot develop freely – that is, if the structure is not isostatic – they produce forces and therefore stresses which, as is true of soil movements, may became very great. Temperature and soil movement exert very significant indirect static impacts in Angkor.

This distinction is important because the criteria of the intervention may be very different in case a) or b).

c). Dynamic impacts:

These impacts are characterised by accelerations which produce forces in relation to the properties of the structure.

Wind and earthquakes produce key dynamic impacts. While wind has clearly an alteration effect on temperature and humidity, it is also important to evaluate the dynamic effect that wind can have on materials and monuments. With regard to accelerations – and thereby forces that are induced on the structures – the massive size and rigidity of the monuments generally prevents the generation of vibrations and any significant impacts that these can incur; notwithstanding, some records on the Bayon towers tend to indicate that they may have some low impacts.

With regard to earthquakes, the structural characteristics that amplify dynamic effects are totally different from those due to the influence of wind action. High masses and rigid structures are the worst possible scenario. Therefore, the temples of Angkor weakened by their unusual structural connections may have suffered in the past and indeed may continue to suffer damage as a result of these kinds of actions. The present damage survey does not rule out the possibility of seismic action.

Unfortunately, we do not presently have any reliable data on the intensity of any earthquakes that may have occurred, although the geomorphology of the site seems to show that it may be subject to tremors. On the other hand, the site was virtually abandoned for several centuries and the record of that time remains silent. Studies and research must be carried out in order to determine whether conservation and restoration projects should consider seismic action and the intensity thereof.

Finally, the monuments could be affected by dynamic impacts such as the vibrations produced by human presence, vehicular traffic and aircraft. At this time, however, it does not seem that aircraft have enough impact to be of concern.

d). Environmental impacts:

Environmental impacts are those induced by the climate (temperature variations, precipitation), pollution, vegetation, tourism, rising water, etc. These impacts may affect the materials themselves (pollution), the structural behaviour (trees) or on both (changes of temperature which can induce deformations and therefore structural problems and at the same time promote the decay of materials). The microclimate change subsequent to tree clearance around the temples should be considered, as such a measure is conducive to the acceleration of stone decay.

Tree roots have been a major cause of damage and collapse in the past. The roots which frequently penetrate and grow in the joints between stones produce forces strong enough to displace blocks, change a temple’s geometry and eventually generate an unstable situation. Preventive and strengthening measures can allow the trees and structures to exist in a symbiotic relationship. A maintenance plan must be put in place to check regularly how things are going.

III. Organisation of the Project

III.1. Introduction

The conservation and/or restoration project should include the following activities, summarised here and then detailed in the following paragraphs:

- **Planning:** This includes the first contacts, preliminary site visits, the definition of the aims and objectives, formulation of the work plan, the budget and schedule and the distribution of tasks.

- **Acquisition of data:** This includes the collection of all data regarding the history of the object to be conserved or restored, its iconography, construction, previous conservation and restoration interventions, social research, and preparation of plans and documentation forms; photographic documentation, picture monitoring, current condition, mapping and documentation of materials, execution techniques, examination of materials and agents of decay. This phase concerns also the preparation of a clear investigation plan, the "anamnesis."

- **Diagnosis and safety evaluation:** On the basis of the acquired data and the structural analysis, the causes of damage and decay and the present safety levels have to be examined case by case and evaluated.

- **Therapy:** Tailoring of the measures to ensure the safety and durability of the structure.

- **Controls:** Quality control surveys implemented during and after the conservation/preservation operations, including a long-term maintenance plan.

III.2. Planning

Before undertaking any project it is necessary to do a preliminary evaluation of the situation, of the risks (and therefore priorities) and of the essential data and conduct investigations necessary to have an initial overview of the building.

III.3. Acquisition of data

III.3.1. Historical research

The first phase of the study should always be an historical research of anything (including partial or total reconstruction) previously done on the monument and of the techniques and methods that were used in the original design and construction of the monument. Consulting historical archives is a very important phase of the study.

The research and analysis phase is decisive in any conservation intervention. All conservation programmes must be preceded by extensive research before any operation is actually begun on site.

This research should cover the largest possible variety of fields, in order to provide planners and implementers of the conservation operation with as much information as possible relating to the analysed site. The fields of research should not be restricted to the conservation of the materials and structures, but should also include historical, social, religious, cultural and environmental factors.

Particular attention should be paid to the dates of the construction and inauguration of the monument and to the various historical periods it has been through. In Cambodia, as elsewhere, a monument might have survived various eras of iconoclasm and changes of religion, and social/religious disruptions.

Only a handful of documented original materials exist and there is very little written on the subject. Inscriptions are common but can often be misleading, especially regarding the dating of the temples. The research should then be a combination of scholarly interpretation of the inscriptions and writings combined with close observation and interpretation of the architectural surfaces and the constituent and restoration materials, which can often yield more reliable information. It should be noted that there have been a number of restoration operations over the centuries and the dating of the materials used could be of great significance.

Particular attention should be paid to areas where there are signs of building modification or superimposition. When it is necessary to make changes or integrations during the conservation/restoration intervention, these must be recorded and explained. They must include documentation that identifies the differences between the historical and new changes. Depending on the context of the object, the level of integration, and any retouching, addition and artificial ageing, must be carefully evaluated.

III.3.2. Survey

The survey includes the geometrical-architectural survey, the structural survey (mapping damage, cracks, deformations, out-of-plumb, etc.) and the material survey (indicating the different kinds of materials and the decay phenomena). Modern techniques are recommended.

III.3.3. Archaeological Excavations

Archaeological research and archaeological test pits should be included in the analysis of the monuments of Angkor and their development over time.

Knowledge of the stratigraphy of the site is an important element in the process of identification of its present condition and plays an important role when deciding on the restoration scheme and designing the conservation and restoration programme.

On a site as extensive as Angkor, the findings of archaeological excavations should be gathered and shared. They should then be integrated in a database, thus providing invaluable documentation in such an historical complex where written records can be complemented by archaeological data.

The original soil mounds of monuments have been found to be very densely compacted on every site where geotechnical studies were performed. In terms of authenticity, the densely compacted layered soil of the man-made subsoil at Angkor is one of the defining elements of the soil structure heritage and must not be changed by later excavations. Furthermore, a loosely backfilled excavation easily erodes and causes ground settlement that results in damage to nearby structures, not to mention posing a danger for visitors to the sites. The backfilling soil and materials must resemble as closely as possible the original soil and materials. Every step of backfilling work must be well documented.

III.3.4. Tests and Investigations

Tests mainly involve the mechanical (resistance, etc.) and chemical characteristics of the materials.

III.3.5. Monitoring

When changes are in progress that may affect the behaviour of the structure, it may be necessary to monitor movement. Unstable soil settlement often requires this kind of control of the mound.

The simplest way of monitoring is through periodic topographic controls and the use of “tell-tales” placed across the cracks (usually small lengths of glass that break when the cracks move).

The hanging of a plumb line to measure inclinations can be a simple and useful tool.

More sophisticated monitoring systems include electronic devices such as fissurometers, inclinometers, etc. connected to a computer-based recording unit. These systems can be very expensive and should be used only when absolutely necessary, for example when the phenomenon in progress could cause serious damage or collapse. The analysis of the diagrams and of the trend of deformations generated by the monitoring systems can usually identify risks before they become too great, allowing remedial measures to be taken in a timely manner.

Monitoring includes the climatic conditions both inside and outside the building and sometimes pollution analysis.

III.4. Diagnosis and Safety Evaluation

Diagnosis and the consequent safety evaluation are key phases of any project because they determine the best intervention choice, or “therapy.” Usually the outputs of the three operations below have to be taken into account together:

- **Historical research** is very important for understanding the monument and therefore makes a major contribution to the diagnosis and evaluation of the condition of the monument.

- **Observation** of the structure, including a case-by-case analysis of the pattern of cracks, the opening of joints, crushing phenomena, detachments, tilting, etc. is essential in the diagnosis and safety evaluation.

- **Structural analysis** of the building in relation to specific problems is the third essential process to be carried out jointly with the historical research and in situ observation processes. It is usually sufficient to carry out this analysis on the basis of a simplified model of the structure.

In complex cases, more sophisticated mathematical models analysed with computer programmes should be utilised. Nevertheless, it must be stressed that more sophisticated mathematical models do not always give more reliable results than simpler ones due to the difficulty of correctly schematising complex phenomena such as the effects of soil settlement. What counts is a correct interpretation of the complex reality of the building.

The results of the diagnostic phase and of the safety evaluation should be clearly explained, indicating the reasons for material decay and structural damage in an explanatory report. This report contains a summary of the main points that have been analysed and in particular of the evaluation stemming from the three processes mentioned above: historical research, observation of the current condition of the monument and structural analysis jointly with material testing. It is important to explain the choices and decisions made in order to justify the proposed interventions.

III.5. Therapy

Therapy concerns all measures designed to improve the behaviour of the structure and the conservation of materials. Therapy can involve the modification of the structural scheme and the replacement of materials.

The kind of therapy selected depends on the considerations made in chapter 2 (minimum intervention, etc.) and on the findings of the diagnosis and safety evaluation. (See paragraph III.4.)

Usually more than one solution has to be studied and the choices are based on what is discovered when undertaking the actions outlined under points II and III.4, taking into account sustainability, costs and any necessary emergency intervention.

The final choice must also be clearly justified in terms of improving the safety of the structure.

Before undertaking any work, it is always necessary to bring together all documentation, including drawings and photos of the condition of the building, in order to be able to verify any modification.

III.6.Controls and Maintenance

Controls are a series of analyses and investigations (including monitoring) to verify – during and after the conservation/restoration work – that the expected results have been achieved. Controls must also be defined in a general maintenance plan that is part of any conservation and restoration project. This plan should include a timetable of the different kinds of actions to be undertaken at different intervals of time.

IV. Material Characteristics and Decay

IV.1. Introduction

This section includes a basic outline of the characteristics of the principal materials used in the construction and decoration of the Angkor temples. The rate and amount of decay is related to properties of the materials and to the environment to which they are exposed. The most common deterioration patterns in materials used for construction and decoration in Angkor are briefly described in this chapter.

As already mentioned, a broad variety of materials was used by the ancient Khmer temple builders. Moreover, it is obvious that environmental conditions are very site specific at Angkor. It is therefore hard to set out guidelines as to the active decay processes, since they vary from site to site and from material to material and frequently result from the complex interaction of numerous phenomena.

Water action is common to nearly all the types of decay observed at Angkor, so an awareness of the impact of all forms of water (rain, water vapour, condensation, capillary uptake, etc.) will assist the conservator in his research into more specific causes of decay.

As a consequence, it is clearly necessary to study in detail the behaviour of the constituent material in the presence of water. What is the porosity of the material and its capacity to absorb water? Clearly identifying the interaction of water with the components of the building material is very important in understanding decay mechanisms that may or may not be active.

Research and documentation on climate and microclimate are also vital. The frequent variations in temperature and humidity are more damaging to the constituent materials than temperature and humidity per se. Therefore, these variations should be monitored at various points throughout a site for a period of more than a year.

Again, this charter aims at providing introductory guidelines for conservators and researchers, and is not meant to overshadow the individual research always necessary in the planning and programming of conservation interventions.

IV.2. Construction Materials

IV.2.1. Brick

The use of brick is common in the earlier temples. Brick is an artificial building material made of baked loam. Khmer bricks are kiln-fired. Depending on their position in the kiln they may have been baked in different thermal conditions. They may show intensive zoning due to burning conditions. A dark grey inner core shows reduced atmosphere during the production. A lack of homogeneity is observed in the varying material properties of the bricks.

The type of clay used and the burning conditions of the bricks found in the Angkor complex result in high variations in colour: whitish, yellow, different shades of red to grey or even black. Their water uptake is moderate to medium; their water vapour resistance low. Their mechanical properties are comparable to many sandstone varieties at Angkor.

The bricks were bound together with tight joints during the construction process. There is only a very thin layer of binding substance to be recognized between the individual bricks. (See chapter VII.2.) The composition of the binder has not yet been thoroughly investigated.

The most prominent deterioration pattern of Angkor bricks is rounding, sanding and fragmentation. They often show micro-biological colonisation.

IV.2.2. Sandstone

Sandstone was extensively used for the building and decorating of Khmer temples and sculptures. Most sandstone varieties found in the Angkor region probably came from quarries located at the foot of the Kulen hills and near Beng Mealea. They consist of layered sandstone of the Middle Jurassic–Middle Cretaceous and Triassic eras. The orientation of mica minerals indicates the bedding structure.

For convenience, the sandstone used for the Angkor temples has been classified into three main groups:

1. The first is a grey to greenish-brown or yellowish-brown sandstone, the most common in the Angkor temples. This is a feldspathic arenite that comes from a variety of quarries. It consists mainly of quartz, feldspar (plagioclase and alkali feldspar) and mica. It is medium to fine grained, subangular and well sorted. The matrix is mainly argillaceous and some of these sandstones contain higher contents of carbonate minerals.

2. The second is red sandstone, as used at Banteay Srei, which is a quartz arenite. It is composed mainly of quartz with small rock fragments with detrital grains rounded and well sorted. The matrix is quartzitic. The red colour is ascribed to the presence of haematite.

3. The third is a greenish feldspathic greywacke, as used in the upper parts of Ta Keo temple, composed of quartz, feldspar, biotite, muscovite and rock fragments.

Type 1 shows higher capillarity and lower strength than the other two types. The decay of the different sandstone types varies considerably. On the whole, due to its mineralogical composition and structure the grey to greenish-brown or yellowish-brown sandstone is most severely affected by weathering. The main deterioration patterns are contour scaling, often with crumbling and flaking, delamination and splitting.

By contrast, due to their mineralogical composition, the Banteay Srei red sandstone and the Ta Keo greenish greywacke are more resistant. Red sandstone tends to develop black surface discoloration, while the Ta Keo greywacke forms thin scales. Both stone types tend to fragment.

All sandstone types are affected by discolouration when they are exposed to weather (blackening of red sandstone, yellowing of grey sandstone and whitening of green sandstone).

The climatic environment of the monuments is a major factor in the degree of sandstone decay on the Angkor temples. Repeated wetting-drying cycles provoke swelling-shrinking movements, hastening sandstone decay. Constantly high atmospheric humidity is more favourable for the preservation of the Angkor building materials than ever-changing climatic conditions.

Photo-monitoring of the decay process of temples deprived of trees reveals an intensification of scale development after the deforestation.

IV.2.3. Laterite

Laterite blocks were often used for monument foundations and for some perimeter walls. Laterite is residual sediment that develops in tropical and humid regions from the underlying base rocks. This type of stone was formed as the result of intensive weathering on a flat area with high temperatures and abundant rain, such as in monsoon regions. Laterite mines are not restricted to outcrops like the Kulen hills or to riverbeds. The material can be quarried from the ground in many areas. It is light and easy to carve when fresh, which makes it a convenient building material. But it is a very inhomogeneous material, not suited for detailed carvings like sandstone.

This material can also be put in two distinct categories. The first is porous laterite which was used at Prasat Suor Prat and for the foundations of Angkor Wat. The large pores were probably filled with kaolinite which was subsequently washed away.

The second is pisolitic laterite which was used in the substructure of Ta Keo and in the perimeter wall of Phnom Krom. It is relatively homogeneous compared to the porous laterite.

IV.2.4. Wood

The use of wood was prevalent in the Angkor area, dating roughly from the 8th to 17th centuries AD. In most cases, this material was used in temple architecture for decoration, iconography and daily tools. Traces of wood doors, pillars, beams and ceilings, along with many postholes, have been found on Buddhist terraces (some temples on Phnom Kulen, Preah Ko, Lolei, the gateways of Angkor

Thom, Angkor Wat, North Prasat Khleang, Phimeanakas, Ta Prohm, Chrung and Top). Recently, a long wooden boat was unearthed in the area of Wat Atvear and is dated to around the 14th century.

All new discoveries of wood at Angkor should be preserved in a suitable place and regular monitoring should be carried out to check the condition of wood vestiges on the temples. Utmost attention must be paid to ancient wood structures in any conservation and restoration project undertaken. The type of wood used in temple architecture, iconography and for daily tools requires further scientific studies. It would be good to build a 3D model representing an ancient wooden historical structure (royal palace or other Buddhist terrace in the Khmer middle period) in the Angkor area to raise public awareness regarding the wooden heritage and give wooden structures a place within the built heritage.

IV.3. Decoration materials

IV.3.1. Stucco

Many brick temples were covered with stucco carvings. This certainly had an important decorative and iconographic function but may have also been applied to protect the brick surfaces which, once carved, are subject to decay.

The surface of the brick was often prepared either by chipping (Preah Ko) or by drilling holes (Eastern Mebon and some temples in Koh Ker) to increase the adhesion of the stucco to the brick substrate.

The stucco was composed of slaked lime, river sand and some organic additives to boost its quality. The sand grains, mostly quartz, sometimes also rock fragments, are different in size and shape. The lime was manufactured from mollusc shells. The stucco was applied while still in paste form and was mostly moulded in situ. It was usually applied in stages, with a preparatory layer on which the design was incised or drawn with charcoal, then a decorative layer and lastly the fine details. The deterioration of stucco mainly stems from the lack of adherence between the different layers. When the adhesion to the brick substrate or adhesion between layers fails, large segments of decoration fall off. Cracking and hair fissures are frequent deterioration patterns. Besides this, granular disintegration caused by the degradation of the binding medium and microbiological colonization, leading to a blackening of the surface, may occur.

IV.3.2. Wall Paintings and Plaster

Many examples of plaster in and outside of Khmer temples are still to be seen. Plaster was applied to both sandstone and laterite walls. Badly finished sandstone walls were given an even surface with a thick lime plaster, while loam plaster has been found on laterite walls. Sometimes these coatings still show remnants of paint.

Brick walls still show remains of very thin washes. Brick temples often have traces of elaborate decoration. Recent studies have shown that not only the outside of 9th and 10th century brick temples were decorated but also their inner walls were adorned in a systematic way.

Many of them showed vestiges of original paintings or polychromatic decoration, painted over thin washes that covered the walls as a preparatory layer. The paint relics reveal either figurative art, floral decorations or decoration systems on monochrome or polychrome walls in red or ochre, sometimes horizontally striped with black. The colours used were all mineral red, black, white and yellow pigments. The patterns bear similarity to the design of outer stucco and stone decorations. The state of preservation of the paintings and plasters is poor; there is a very high risk of losing these traces of decoration due to human impact (such as visitors leaning on the walls).

Due to the failure of the roofing and the impact of water in addition to wear caused by human activities, very few traces of these decorations remain. The stress caused by rain and damaging salts is high. The main deterioration patterns are: loss of paint layers, salt crusts, discolouration and staining. Powdering and flaking of the paint layer is also observed. Microbiological colonization is widespread.

IV.3.3. Polychromy

Traces of paint are apparent on surfaces at each period of the history of Khmer architecture. These traces might be either preliminary sketches that helped to plan regular tapestry-type decorations or long bas-relief sequences or a real polychromatic decoration of different surfaces. Iron red and ochre, white and red lead, cinnabar and gold have been analysed as pigments. The binders sampled consist of calcium carbonate with perhaps the addition of organic substances.

In some cases, the paint was applied directly to the surface of the sandstone, brick or stucco; in others, there was a preparatory layer.

Lacquers were also used to decorate walls and sculptures. An Angkor Wat inscription mentions that lacquer was applied to statues during post-Angkorian restorations. There are traces of gold on the bas-reliefs of Angkor Wat and on the more important religious images. Sometimes this is in the form of gold leaf, either from a final treatment layer put on during post-Angkorian restorations or from the votive offerings of pilgrims.

V. Material Conservation

V.1. Introduction

The deterioration process of a monument can be delayed considerably when specially tailored preservation tools are applied. Conservation and restoration plans have to consider all individual requirements of the object. These have to be elaborated for each monument and include the subsequent maintenance programme. It is impossible, however, to stop deterioration processes completely.

All conservation interventions carried out on materials at Angkor must be preceded by careful phenomenological surveys including documentation and analysis of all materials on site, their distribution and their state of preservation. Special attention has to be paid to hollow scales and detached layers, which might require emergency interventions.

The presence of damaging salts and humidity at the site must be documented. It is important to note the formation of crusts, biological colonisation and former conservation measures (i.e. waterproofing). Non- or minimally destructive investigations help to confirm the results of the visual survey. The nature and depth profile of damaging salts has to be analysed. Once the material properties, the type and the degree, as well as the causes, of the decay have been established, it is possible to plan the implementation of appropriate techniques and materials to ensure the best possible conservation.

The design of preservation plans follows a system as shown in chapter III. After the initial planning process, including on-site visits and discussions, the “anamnesis” starts. All available information on the monument including its building and restoration history is collected and reviewed.

The anamnesis is followed by analysis and diagnosis. The analysis covers all aspects of the monument’s condition and materials. It comprises investigations into static problems, construction materials, the state of deterioration, as well as climatic, geological and environmental conditions. A thorough photo-documentation of the condition of the monument is made. All important items must be recorded and mapped. Thus, static problems, use of materials (the types of stone, plaster, concrete and polychromy) as well as the deterioration patterns and their degree must be registered and depicted.

After the analysis is completed and all results have been assessed, it is possible to move into the design of the therapy.

At the beginning of the therapy phase, appropriate interventions and materials are selected, then laboratory and on-site tests are performed. Interventions that have been tested and proven to be successful are included in the preservation plan and executed. A complete intervention must be followed by a quality control and evaluation process. Subsequent maintenance and up-keep of the monument are absolutely necessary.

The laboratory and on-site testing of methods and materials is the only way to guarantee that the conservation procedures and materials are safe to use. A conservation intervention must never be allowed to cause any additional damage to the materials preserved; they must not introduce any damaging substances to the object or change the original properties of the construction materials. Some products may have negative side effects in terms of compatibility or long-term behaviour and may in fact cause new damage to the material treated. Possible negative effects of new products have to be considered.

Conservation measures are tailored therapies designed for a specific material and a special situation that have been investigated in detail upstream. Skilled and talented conservators are essential for implementation.

Conservation activities must always be followed by a quality control and a maintenance programme that should be considered as an integral part of the whole conservation process. Measures that are not carefully tested and thoroughly carried out can often incur damage far beyond the deterioration phenomena that were to be treated.

V.2. Systematic Planning of Conservation Interventions

Conservation interventions, as already stated, must be preceded by a careful preparation phase, including thorough documentation and scientific research. A detailed mapping and documentation of the materials, of the state of preservation and of former interventions are the first tasks.

Based on this first assessment, a risk map of the monument is compiled. The risk map estimates the levels of decay of the stones, carved surfaces and the like. It plays an essential role in the first step of planning and implementing an effective conservation programme. For successful conservation, a thorough knowledge of the material, its properties, and preservation condition is most important.

Based on the risk map, a list of priorities can be compiled. This priority list combines an estimation of the risk with the historical value of the monument and the importance of the individual members of a monument. The order of restoration of the elements is defined on the priority list. (See chapter IX.)

Both planning tools – the risk map and the priority list – enable implementation of a systematic conservation project for the individual Angkor monuments.

V.3. Preliminary/Emergency Consolidation

Emergency consolidation or preliminary consolidation is an essential first phase and can determine the success of the overall intervention. It can be carried out at the same time as other phases of the conservation intervention. Emergency interventions help to hold highly endangered pieces in place and prevent their loss. Like all conservation activities, they must be carefully planned and implemented. Emergency conservation activities have to be fully reversible, since the emergency stabilisation is removed after the full conservation programme has been completed. Emergency consolidation procedures must not impede the implementation of the conservation programme or conflict with methods and materials. Only materials that will not alter while they are in situ may be applied.

V.4. Cleaning

Stone cleaning may be a necessary conservation procedure in the following cases:

- Presence of damaging salt crusts.
- Presence of dense layers on the stone surface.
- When the readability of reliefs and architectonical elements is severely reduced.
- When the application of essential conservation methods and materials may be impeded.

It is sometimes necessary to remove materials used during previous interventions that proved to be damaging, such as Portland cement or reinforced concrete repairs and coatings of acrylic resin.

For stone cleaning procedures, different cleaning methods are adapted to the conservation needs of the Angkor monuments. The decision for a specific method has to be based on a prior examination of the on-site situation. Before any cleaning procedure can start it has to be clear that no polychrome layers or mural decoration are present. These important pieces of Khmer culture would be destroyed by the cleaning activities.

V.5. Removal of Microbiological Contamination and Biocide Treatment

Biological attacks can induce material deterioration. Both the protective versus destructive action of biological agents should be carefully assessed before considering the removal of micro¬biological contamination and the means used. In particular, although the active growth of lichens can cause chemical weathering of stone surfaces, lichens have been shown to act protectively by buffering stone surfaces from thermal stress and direct water intrusion.

Angkor is situated in a tropical monsoonal region with very high microbiological activity. Cleaned surfaces will be re-colonised after a very short time of natural exposure. Under such conditions, no organic or inorganic biocides/chemicals can be recommended for use to inhibit the microbial colonization effectively.

Microbiological studies at Angkor Wat and of surrounding temples on the Angkor site conducted by international teams have revealed that the natural micro-flora on stone is made up of a complex and stable microbial community of algae, fungi, lichens and bacteria, the distribution of which is widely controlled by moisture conditions.

Organic biocides and those containing chloride should be avoided because of their toxicity, their lack of long-term efficacy and possible nutritive effects for the reoccurring micro-flora. The application of microbial-resistant stone protective agents must be compliant with international standardized testing and proper hygiene at the site. Conservation activities need to be supported by measures to ensure protection from water runoff and infiltration. Again, the long-term effectiveness of any conservation treatment must be ensured by ongoing maintenance and care for the monuments and temples.

V.6. Salt reduction

Salts in the pore spaces of minerals of the materials used for construction and sculptures have various sources.

Most salt load derives from environmental or biological impact such as air pollution or colonisation by animals (bats, birds, etc.). Additionally, salts arise from the material itself. Stone, bricks and mortars including stucco have a natural content of salts. Besides, the properties of modern restoration materials like Portland cement or some hydraulic limes are such that they charge the object materials with an additional salt load. Different salt minerals develop their own peculiar damaging attacks on the materials.

Salt reduction may become necessary in Angkor when:

- There is evidence of damage provoked by soluble salts.
- The application of essential conservation methods and materials is impeded.
- Sustainability of the conservation measures is hampered by soluble salts.

Salt contamination must be analysed at the surface and in a depth profile; the chemical (anions and cations) and mineralogical components of the salts have to be determined. Compact salt crusts may be reduced by the careful use of mechanical procedures such micro-particle blasting or by the use of a hydraulic micro-chisel or ultrasonic chisel. Scrupulous cleanliness at the working site is absolutely compulsory in order to prevent the removed salts from re-entering the treated area.

Salt reduction is also made possible by the repeated application of desalination poultices. These poultices have to be adapted to the pore size parameters of the stone, brick or mortar to which they are applied.

The most common and effective poultice materials are cellulose fibres, special absorbent clays or paper pulp. The poultices are mixed with de-ionised water. Depending on the salts present, salt reduction can be carried out either by leaving the poultices to dry or by the application of permanently wet poultices. Salt reduction by poultices is always combined with a water flushing of the material. This has to be considered before making a decision for or against a salt reduction measure. In the climate peculiar to the Angkor region, a special effort is required to prevent microbiological contamination of the poultice material.

V.7. Consolidation

Weathering of building and decoration materials over long periods can lead to a destabilised outer zone. Consolidation can bring back mechanical strength to the material if weathering has considerably weakened the cohesive forces of the mineral components. The extent of the deconsolidated zone depends on the material properties, the environment, weathering mechanisms and time.

Impregnation with consolidants adapted to the mechanical strength of the weathered zones can be used to achieve the strength of non-weathered material. Different consolidation agents are on the market. The former use of artificial resins for consolidation provoked considerable damage and should not be a tool for conservation in Angkor any more. It is recommended that the reaction product of a consolidation agent should be chemically similar to the treated material.

Consolidation by impregnation is carried out on Angkor monuments in order to stabilise sanding and flaking surfaces and brittle zones behind hollow scales. Pointing mortars can also be consolidated in order to give them greater strength and resistance to weathering as well as to enhance their adhesive qualities with the substrate.

Consolidation by impregnation also requires careful planning. A site selected for conservation must be protected from rain, as wet materials cannot be impregnated. In Angkor, such protection should be set up on a site for conservation before the start of the monsoon. Also, the technical instructions of the producer of the consolidant used should be followed.

As with all conservation interventions, there are requirements to be fulfilled in order to perform a safe conservation operation and minimize the risk of damage being caused by the intervention.

It is very important to grasp the strength and elasticity profiles re-established by the consolidation achieved through impregnation. Here, a moderate enhancement with a homogenous transition to the interior of the stone is indispensable; otherwise, an over-strengthened scale will be produced which will favour further detachment. In order to achieve a homogenous strength profile, previous tests on site and in laboratory are necessary. First of all, the depth of the deconsolidated zone has to be determined on site and equivalent material has to be consolidated in laboratory to select the consolidation agent, the amount of agent needed, the length of the treatment and the success in achieving a homogenous strength profile.

V.8. Injection of Scales and Pointing

The development of contour scaling is the most prominent and dangerous deterioration pattern affecting sandstone on many Angkor monuments. Scales can also occur on bricks. Longer members such as door jambs made from sandstone tend to show delamination. Stucco decorations tend to suffer loosened contact between individual layers and also with the brick substrate.

By injecting and re-attaching loose scales and separated layers with specially adapted mortars, the endangered parts are retained and water, humidity, and thermal transport is re-established. Scale margins are stabilised; holes and joints are filled by stone repair mortars. Thus, the loss of precious reliefs can be prevented.

Stone repair mortars consist of binding agents and fillers. For conservation operations on the sandstones of Angkor, siliceous bound mortar systems have been developed so that chemically compatible conservation materials are used. Prepared and applied by skilled conservators, they have yielded very good results.

These mortars must be prepared with fillers composed of carefully graduated stone aggregates and dust or washed sand and other fillers such as fumed silica. They are prepared with very precisely defined grain size distributions. This is done by crushing local natural stone or sand and then separating the different grain sizes with calibrated sieves. The recipes have to be modified depending on the types of stone used in the particular temples at Angkor. Before starting the intervention, the best possible grain size distribution and exact binder-filler proportion need to be established. They must be specially adapted to the needs of each monument. Mineral binders such as ordinary lime and hydraulic lime have been used with some success for the conservation of brick structures and for safeguarding stucco elements at Angkor. Further research in this field is ongoing.

Nearly all repair mortars need a moist-curing in order to support a complete reaction. For all mortars, conservators must follow precisely the recipes prescribed for the intervention. The technical recommendations of the producer likewise must be followed.

The properties of the repair mortars applied must be specially adapted to the substrate parameters and the state of deterioration. Above all, mechanical properties such as Young's modulus of elasticity and the compression strength have to be lower than those of the original substrate in order to avoid damaging effects caused by the repair mortar.

V.9. Waterproofing

There are different ways to protect building and decoration materials from rainfall: Build shelters such as roofing, repair existing roofs, install metal coverings, etc. or impregnate with a water-repellent agent. The first possibilities should always be preferred.

Water repellent impregnation aims at the reduction of water uptake without influencing the water vapour diffusion behaviour of the materials. It is important to realise that only capillarity is impeded; other damaging influences such as salt contamination or hygric swelling are not reduced by this treatment. Today, the most common water repellents used are based on different formulations of silicone.

A water-repellent treatment may only be considered after strong damaging effects caused by rainwater and sufficient capillarity of the stone have been proven. Hydrophobic treatments are not long-lasting. The impregnation has to be repeated after a few years. Repetitive impregnation can change considerably the properties of the treated materials.

For a decision in favour of a water-repellent treatment, several preconditions concerning the building materials are mandatory:

- No presence of expanding or swelling components, e.g. clay minerals.
- No presence of dense surfaces due to sinter, salts, crusts or intensive bio-colonisation.
- No presence of hygroscopic salts.
- No contraindication due to former conservation interventions or decorations.

Most of Angkor’s stone materials contain swelling clay minerals and therefore bear a high risk of sequential damage after treatment with water repellents. Many surfaces are dense due to various degradation and decoration impacts. Salt load is ubiquitous in the building and decoration materials of all Angkor temples.

Water infiltration is omnipresent and uncontrolled in the temples; this is due to the construction method used for the Khmer temples that feature dry joints without jointing mortars, with false vaults and low foundations. The position of the temples renders them subject to frequent humidity uptake. Large bat populations, whose guano produces damaging salts, have led to a high soluble salt contamination in the structures they inhabit.

The building materials used on Khmer temples do not generally lend themselves to a safe water-repellent treatment, so such a treatment may be more damaging than protective.

V.10. Washes and Sacrificial Layers

It is sometimes necessary to smooth rough, deteriorated surfaces in order to reduce the reactive surface area of the materials. This can be done through the application of specially prepared thin washes. Washes are very thin mortar coatings (around 5 mm) that protect and sometimes also consolidate the weathered stone surface. They do not conceal the visual appearance of the underlying stone substrate.

Washes are used in the Angkor monuments to stabilize flaking and sanding surfaces and to reduce weathering by reducing the reactive surface. Normally, they are applied as the last step of a stone conservation intervention in order to protect and equalize the properties of the surface. Brick or stucco may also be protected by a wash.

V.11. Quality Control and Maintenance Programmes

Quality management of conservation interventions is essential. The performance of the methods and materials has to be verified before, during and after the intervention. The success of the conservation operation has to be assessed and, when necessary, interventions have to be redone or repeated. Several non- or minimally destructive testing possibilities (e.g. water absorption measurements by Karsten pipe, ultrasound velocity tests or drilling resistance measurements) help evaluate the results of the conservation intervention. A monitoring plan is necessary in order to verify the long-term durability of the measures.

Maintenance is another essential part in safeguarding and preserving archaeological sites. For the Angkor monuments, maintenance means, for example, monitoring trees and their roots, removing small/new plants from the building structures, cleaning the walls of dust, dirt and insect nests, securing endangered parts such as surfaces scaling off, repairing open joints where water seeps in and, last but not least, small repairs. All this has to be carried out with the utmost caution in order not to provoke new damage when maintaining the monument. An efficient maintenance programme must be put in place, with a precise timetable for different kinds of controls and activities to be carried out at different intervals.

VI. Soil, Water and Environment

VI.1. Climatic Conditions

The Angkor region is subject to the typical monsoonal climate of Southeast Asia, the effects of which are being exacerbated by climate change. The prevailing winds blow from the south-west in summer and bring evaporated water from the Indian Ocean. The rainy season starts in May and ends in October, with an average rainfall of 200 mm/month.

The dry season generally runs from November to April with an average rainfall of 50 mm/month, with north-east prevailing winds from China. At the end of the dry season, the temperature can reach highs of about 40°C.

The daily temperature and humidity cycles exert mechanical stresses on sandstone materials and induce severe decay.

Wind can be also an agent causing the decay of stone and masonry in Angkor for a variety of reasons.

VI.2. Vegetation Cover

The vegetation of Angkor is dominated by a semi-evergreen forest which has become part of the region’s cultural heritage. Although individual trees may threaten the stability of archaeological structures, the forest as a whole plays a protective role. Firstly, by creating microclimatic and drainage conditions conducive to soil stabilization and stone conservation. Secondly, by favouring the growth of lichenified films below which stone bio-deterioration operates much more slowly and superficially than on stone surfaces directly exposed to sunshine and monsoonal rains, which are subject to severe inorganic mechanical deterioration. This buffering role of the forest and lichen covers should be considered and their removal avoided in order to favour the preservation of the carved sandstone surfaces or, at least, to delay their decay.

VI.3. Water System

The water system plays a key role in environmental balance. The Angkor civilization partly developed as a result of the construction of water facilities enabling it to take advantage of the heavy rainfall. The construction of embankments, reservoirs, dikes, weirs and sluices, often around the main religious buildings, facilitated abundant harvests and reduced flooded areas.

The correct management of water resources not only meant that the activities of the Khmers thrived but also helped them to control the behaviour of constructions in areas exposed to soil settlements due to local variations of the groundwater table. Reservoirs such as barays or srah helped in the regulation of the ground water table and consequently mitigated building foundation deformations. Thus, after the decline of the Angkor empire, the lack of water infrastructure maintenance and its subsequent silting up led to the loss of monsoonal flood regulation. This caused heavy water table level variations, inducing severe damage to the structures and their foundations, instability of the embankments and acceleration of material decay.

VI.4. Soil

The superficial soil of Angkor consists mostly of alluvial deposits made up of layers of fine sand and layers of silty and clayey sand or sandy silt. In between these, frequent inclusions of silt, originating from soil erosion and transport have also been reported. The water content is about 12–25 per cent.

The top surface soil dates back to Quaternary deposits and measures about 40 m in thickness. It is followed by weathered sand/tuff stone belonging to the Cenozoic era. The base rock is of volcanic stone and/or sandstone of the Jurassic Period (Mesozoic) at depths of about 70 to 80 m from the surface.

Results of soil investigation have mostly been provided by geological and geo-technical surveys made by JSA (Japanese Organisation for the Safeguarding of Angkor, JSA Annual Reports, 1996 and following). Similar types of soil can be inferred for other sites of the area, where this data can be used before the start of a comprehensive survey campaign covering all of the Angkor area.

The soil supporting the foundations of the temples plays a key role in some of the most common structural behaviour and damage patterns.

Oscillations of the water table are normally related to the water level of the nearby rivers, lakes, dikes and/or reservoirs and are related to variations in their levels. The level can vary by several meters between the dry and rainy seasons. This usually results in soil settlements, chiefly depending on their silty content and the compressibility of the soil.

VI.5. Ground and Water

The Angkor area lies between the Kulen hills, about 40 km to the north, and the lowlands of Tonle Sap Lake on the shores of which stand the southernmost temples.

The headwaters from the Kulen hills flow across this gently sloping terrain, running through waterways on the surface and in hidden channels below, according to soil permeability and the principle of filtration. The water table reacts immediately to rainfall on its top surface layers, whereas the deeper layers are hardly affected. The permeability of the soil is in the range of 10 cm3/sec. The average slope of the ground surface is 1/1000. The velocity of the underground water is extremely low, about 31 m/year.

As the natural water flow is very slow, the annual fluctuation of surface water in the ground is due to infiltration and evaporation.

During the dry season the water table level goes down to 3 m and can go as low as 5 m from the ground surface by the time the monsoon returns. In other words, during the dry season the superficial layer of the soil, 3 to 5 m thick, dries and becomes very hard.

The soil contracts during the dry season and swells in the rainy season. The volume change is one of the main mechanisms causing deformation of masonry structures. As much as 3 to 6 mm of settlement and heaving at the ground surface due to contraction the rainy season and swelling during the dry season have been observed, with the underground water level varying by around 3 m.

Rising water levels in ditches and trenches are most likely to trigger the sudden collapse of embankments, especially during the wet season, when heavy and prolonged rains are frequent.

A rise of the water level in sandy soils results in higher general stresses and lessens the mutual frictional forces between the grains, as those forces depend on the effective stresses. Sudden landslides and local instabilities can be induced by water seepage from uphill to down-hill, aggravated by low drainage conditions. This circumstance can trigger a chain process that starts with the partial collapse at the foot of the submerged slope, now fully saturated.

The basins and moats around the temples play an important role in their architecture. The basins are surrounded by earth embankments, often faced with tiers of stone leading to the water. The behaviour of these embankments has often induced the displacement of parts of temples located nearby. Sudden variations of moat water levels, mainly due to heavy rainfall, can cause instability in the embankment due to low permeability and the lack of drainage inside the earth mass. Attention must therefore be given to the pore water pressure in the soil resulting from the rapid variation of water level in the reservoir in order to better assess the safety margin of the earth structures.

Numerous examples of these phenomena are present all over the Angkor area, and especially tier-faced reservoirs (Angkor Wat moat, Srah Srang pond, etc.).

Flow-out of the soil of the embankment into the moats is common in the Angkor area. One of the possible causes is the phenomenon of piping that begins at the front of the embankment. If seepage velocity at the outgoing surface exceeds a certain value, the soil is washed out. This is the start of piping that is followed by continuous erosion of inner soils and ends up forming a pipe in the embankment up to the surface. Behind the upper terrace stones, cavities can be formed as a result of this water and soil flow-out.

VI.6. Urbanisation and Infrastructure

Human intervention, with the construction of canals and water reservoirs since the first Khmer royal capitals were settled in it, has altered the hydro-geological equilibrium of the area. Lately, the rapid urbanisation of the city of Siem Reap, once a small town, has triggered substantial new variations in the overall water balance, as the population has increased at a much faster rate than the related infrastructure, with significant volumes of natural water being pumped from the soil.

The differential settlement of the ground is the key element in the damage suffered by masonry structures. The pumping of underground water by hotels has had a heavy impact, lowering underground water levels. A monitoring system measuring the underground water level near the monuments should be established, as well as the organisation and control of the wells in Angkor to reduce the dangerous effects of ground water oscillation on the monuments.

The yearly fluctuations or seasonal changes of the water table are the most common cause of concern, but major changes developing over a larger time scale can also affect soil behaviour, such as during long periods of drought or in the case of artificially introduced modifications of soil water content. Deformations can develop from 10 to 30 years after the variations have been introduced, depending on the properties of the soil involved, local conditions and layer stratification.

VI.7. Soil Settlement Induced by loads

As the water table is close to the surface all year round, some soil deformation can actually be linked to the direct load of the superimposed constructions, due to the low level of effective stress. In the soil layers directly under the construction, the volume of soil supporting the imposed external load gets larger with increasing depth, and the related pressures decrease accordingly, whilst lithostatic pressures increase.

As a rule of thumb, the influence of the external load can be considered important up to depths corresponding to the footprint of the construction. In the case of a man-made mountain temple, this value can be sizeable.

Uniform deformations are not prone to induce any damage to a structure when such occur along a vertical axis with a rigid translation which does not affect the overall integrity or equilibrium of the structure. Nevertheless, deformations are rarely uniform due to the irregularities of deposits and soil stratifications and to uneven stress distribution. In fact, the load distribution theory for a finite load contact area yields uneven tensions even in the case of homogeneous soil.

For strata found deeper than the mentioned reference length, the soil's own dead load prevails over other factors.

VI.8. Subsidence

Soil volume reduction without significant load change, referred to as subsidence, is a common phenomenon in Angkor soils of medium to fine grain. It is regulated by the initial water content and density of the soil, its permeability and boundary conditions or compressibility. It is a slow process of water expulsion from the particle matrix of the fine soils leveraging onto the internal structural soil variations.

As in other soil-water related settlements, subsidence induced deformations are generally irreversible. Such phenomena, if rationally approached, can be dealt with. Draining wells or trenches, strategically positioned and cleaned, can counter unfavourable deformations or tweak favourable ones.

VI.9. Damage and Progressive Failure

There is a high potential of collapse if internal soil friction strength is reduced. Due to the constitutive laws for soils, namely for dense, rigid soils, phenomena of progressive failure take place, characterised by large displacements bringing earth structures such as natural slopes or artificial trenches to their complete collapse.

Even after large displacements, though, soil masses can reach a new equilibrium. Greater loads induce movements, as is usual in the case of the swelling of foundation soils. If the structure is subject to soil displacements, this can compromise the use/function of the structure, although it does not alter the structural bearing capacity. Differential soil settlements of the foundations can lead to two main phenomena:

- Leaning if the tower is sufficiently rigid or the different settlements of the foundations are linear.
- Vertical cracks, usually associated with outward deformations of the walls and slippage between the blocks (or bricks), if the differential settlements are not linear. See paragraph VII.6 for further comments.

VI.10. Tunnel Erosion (Piping)

The phenomenon of seepage is closely related to the previously mentioned phenomenon of progressive failure, occurring when fine soils are involved, following the build-up of a head of water, the value of which depends on permeability and the direction of the flow. It causes the lifting of a portion of soil submitted to backpressures by the water flow.

The building of a head of water should be avoided by diffused drainage, or opposed with adequate friction forces. Its occurrence can cause the sudden collapse of structures.

Typically, a change in the composition of the seeping water from prevailing sandy soils to prevailing fine silty layers causes a water pressure surcharge, as the different filtration velocity through the ground concentrates pressures at the back of the "less permeable" layer faster than expected.

The infiltration of rainwater into the deeper ground levels should be prevented in those cases where water-related neutral overpressures are expected to cause such problems. Putting in trenches that can gather superficial runoff water and the creation of gentle slopes can also be encouraged.

VI.11. Erosion

Superficial erosion of the soils caused by water flow over the ground during intensive rains is not much of a problem in the short term, as superficial vegetation constitutes a natural protection even for monsoon rains.

On the other hand, washing out of the filling from inside a retaining structure causes a gradual depletion of its volume. The integrity of the construction can be affected in the long term by loss of backfill as the process is continuous and localised and eventually causes uneven force contact stress distribution. The phenomenon of diminishing foundation volume can be confused with soil settlement.

This is a common and serious problem in the Angkor area and must be solved by filtering the drained waters to prevent the transport of solids from inside the structure and/or protection from infiltration by appropriate covering.

VI.12. Earth Structures and Embankments

Special attention has to be given to the earth structures that played a big role in the water-based civilisation of Angkor. In the various types of hydraulic works the earth structures are alternatively made of sand, silty sand or even by sandy silt, generally with a low degree of plasticity. The main feature of these structures is that they are very sensitive to the variation of the water pore pressure in the soil in the rainy season and to the water level in the reservoir which the embankment confines.

Depending on the excess pore pressure against the water level outside, the unbalanced forces can produce the collapse of the soil. This can result in greater or lesser degrees of deformation or even in the complete collapse of the structure. The Khmer constructive use of backfill behind earth retaining structures, as found in Angkor Wat, has shown the presence of horizontal clayey layers as draining beds for the percolated water. When the water cannot pass through the earthen structure curtain, this can cause the collapse of the structure.

VI.13. Drainage

The various drainage mechanisms of the Angkor monuments aim to evacuate water from the inside to the outside of the monuments, but in some temples the actual drains were only meant to evacuate the sacred waters used for religious purposes. Drainage devices consist of troughs, drainage holes and sinks. Drainage holes are found below the pavement and are tunnelled under galleries.

If the drainage is insufficient or functions badly, rainwater seeps into the laterite foundation blocks and soil backfill. This infiltration results in the increase of the soil water content, consequently weakening it. Laterite blocks are particularly vulnerable to the wet/dry cycles and weathering processes. The bases of most of the masonry structures in Angkor are made of laterite blocks. The weathering of laterite bases and foundations has caused the displacement of upper parts of stone structures. In the case of the Bayon temple, soil has been washed out and this has induced the displacement of the foundation mass, eventually leading to the displacement and consequent inclination of the upper stone structures of walls and towers. It is important to study the ancient drainage system and restore it if appropriate or improve it if is found to be inadequate.

VI.14. Foundations

Constructions in the Angkor area are directly supported by the superficial soils. When built on man-made bases, the backfill was often a compacted laterite and sand mixture. The major problem of foundation settlement comes from direct contact loads and the deep layer behaviour of the soil, as mentioned.

Widening of the foundation base can be a solution when the foundation damage is caused by the high peak stress value, but is not effective for deep soil strata. The introduction of a new foundation base or the enlargement of the existing one can only be effective after the loads are transferred to the new structure. Further settlements are to be expected after the construction of the new base until a new equilibrium has been reached.

VI.15. Retaining Structures

Retaining structures are normally of the gravity type, as wall stability is achieved by the weight force that counteracts leaning due to the earth thrust and by the friction shear strength against the sliding failure mechanism.

They consist of laterite blocks upon which sandstone blocks are set for the upper layers. The lack of monolithic blocks frequently leads to plastic deformation and distortion with tilting of the upper blocks. Retaining structures are often built to contain backfill which supports part of the temple structure. Therefore, it is not always easy to decouple the different functions of a retaining structure from that of a foundation structure.

VI.16. Mountain Temples

Mountain temples are artificial hills, one of the first Angkorian constructions, probably built with the excavation material gathered from the hydraulic works and with superficial sandy soil. These mountains were built from the bottom with gradually smaller terraces up to the top tier, some 20 to 25 m above the ground level. Inclination of the slopes reaches 45° on the flanks of these hills. The natural slope stability theory yields a greater safety factor, as the internal friction angle and cohesion of the soil increase.

The stability of the complex was achieved by positioning a retaining wall structure made of stone blocks simply assembled on top of each other without any mortar binder. Many such gravity walls show signs of damage. Reconstruction and strengthening have been implemented using different approaches, ranging from anastylosis to reinforced concrete walls.

The original Khmer building technique of loose joints between adjacent blocks provides drainage for infiltrated water and prevents the building of a water head at the rear. The blocks were usually cut from laterite stone, a porous material that allows hydraulic transition through the contact surfaces.

Where reconstruction using old collapsed blocks has been done using a sealing mortar but without adequate alternative drainage, impermeability to water has often compromised the overall stability of the structure.

Laterite is a material subject to wearing, and peak tensions resulting from differential soil settlements have often caused deterioration and breakage of the foundation blocks.

Heavy towers are often positioned close to the outer edge of the terrace, adding an unbalancing surcharge to the structure.

VII. Structural Behaviour and Damage

VII.1. Structural Characteristics

All Khmer constructions are built with horizontal courses of either brick or stone. For openings, bricks or stones were placed progressively in cantilever. Arches, vaults and towers are also built using this technique. Some vaults and openings were reinforced with wooden beams which decayed and were thus lost over the centuries, thus weakening the structures.

VII.2. Brick Construction

The pre-Angkorian temples were usually constructed of brick or with mixed materials, brick for the mass and sandstone for the more important details such as doors or lintels.

The mass of the temple was built and then carved later. This technique of putting in the basic form of the building and then finishing the details in situ is a characteristic of Khmer architecture. It started with brick temples and was then elaborated on and refined as the use of stone increased.

The question regarding the binder of the bricks still needs to be definitively answered with further scientific research. At present, two main theories have been proposed regarding the binders used by the ancient Khmer builders in the brick temples:

- **Lime-based**
  The bricks were wetted, a small amount of slaked lime was added and then they were vigorously rubbed together, as indicated by the traces of abrasion in the joints. This created a strong, tight joint that would allow the bricks to be carved later without breaking the joints. The lime was probably made from burning mollusc shells from the Tonle Sap, although a recent study has shown that slaked lime can also come from Battambang and Kampot.

- **Natural resin-based**
  Research by the Lerici Foundation working on the Cham temples at My Son in Vietnam has shown that an organic binder was used. This resin comes from the tree Diptherocarpus Alata, known in Cambodia as cheateal. The resin is commonly used today for the caulking of boats on the Tonle Sap. Tests have been made recently in Cambodia and the initial conclusion from the findings is that the same resin was used by ancient Khmer builders.

Since the carving of bricks removes the baked surface layer and exposes the softer core, there was often a need to strengthen the core of carved bricks by inserting small fragments of brick to replace decayed material.

Surfaces were also treated with a mortar of fine-grain brick dust and lime which formed a strong smooth, uniform surface layer to protect the bricks.

The bricks were always laid horizontally so that when openings were required, a corbelled arch was used. The lintel, usually made of stone, therefore carried a small load. The bonding was quite arbitrary and series of vertical joints are often found. This technique is more evident in dry stone structures.

VII.3. Sandstone Construction

The technique of rubbing that was begun with the brick temples was developed further as the Khmer architects began to favour sandstone and the technology was adapted accordingly.

The bas-reliefs at the Bayon temple give a clue to how this was achieved. The upper stone was suspended over the lower stone using a gantry and lever system that enabled the upper stone to be swung backwards and forwards until the two surfaces became smooth through mutual abrasion. Sandstone lends itself particularly well to this technique because it is rich in abrasive silica.

This again produced tight coursing which increased stability and allowed the surfaces to be carved later without flushing the corners of the blocks at the joints. However, it also meant that the basic premise of Khmer architecture was the horizontal joint and one result of this is the characteristic corbelled vault.

Most architectural details were carved in situ, including window openings, small round columns (colonnettes) and lintels, as well as all decorative elements such as bas-reliefs.

The horizontal joints, and therefore the corbelled blocking techniques, give a peculiar structural behaviour. In principle, the line of the compression forces should be as close as possible to the vertical line (perpendicular to the joints), in order to eliminate the risk of sliding on the joints. Instead, due to the curvature, the inner forces are inclined so that shear forces are created (tangentially to the joints) and this could exceed the friction and produce slippage between the joints themselves. To prevent this damage, it is necessary to have significant vertical forces and therefore heavy structures. As a consequence, the structure takes the shape of a “tower” instead of that of a “dome,” as is common in Europe, where the joints are usually built radially to eliminate the risk of sliding.

VII.4. Laterite Structures

Foundation structures normally consist of a base made of dry bedded laterite blocks. The dimensions of the single blocks are more or less standard. The soil behaviour can produce very high strains on the masonry the strength of which strictly depends on the shear strength and therefore on the friction between the blocks along the joint surface. When these are altered or decayed due to weathering effects, the friction is easily reduced, causing movements and damage, especially if soil settlement is not uniform.

VII.5. Structural Damage

Brick structures, compared to dry block structures, have a more uniform distribution of strength because the binder that connects the bricks provides a certain shear resistance on the horizontal joints. Therefore there is little slippage between the bricks. When stresses exceed the brick strength, cracks are produced following lines generally perpendicular to the main tension stresses. In addition, the strength can be reduced by material decay.

Dry stone buildings are different because the structure is rigid until a point where the shear forces on the joints are lower than the friction. Relative movements between the blocks can be produced only when the shear forces exceed the friction. Large relative movements can cause collapse of the structure.

Stresses inside the structure may be produced by processes of decay, the action of tree roots, etc., but the main cause is related to soil settlement, to the outward deformation of retaining walls of the terraces and to vertical movements or rotations of the foundations. Lightning is another cause of damage to the structures.

The relative movements on the joints alter the contact between stone blocks, creating slippage and/or concentration of the mutual actions along lines or single points (instead of having distributed pressures on the original contact surfaces), so that as the phenomenon progresses cracks are produced that reduce the bearing capacity until the whole structure becomes deformed and eventually collapses. (See paragraph VII.2 below.)

Crushing phenomena are usually concentrated on specific zones, where major deformations or structural detachments have significantly increased the compression stress. This phenomenon is frequent in pillars that support lintels and pediments which, due to their weight and to the general deformations, gradually become detached from the main structure.

Crushing phenomena are exacerbated by the relative inclination between the acting compression force and the bedding plane of the sandstone and brick masonry.

VII.6. Damage Produced by Soil Movements

Usually soil deformations are not uniform. Even when they appear to be uniform, it is often the solidity of the structure that forces it to move rigidly, that is with uniform or linear deformations. In these cases, however, stresses, mainly horizontal, are progressively accumulated in the structure and as soon as they exceed the strength, cracks and major damage appear suddenly.

In tower structures in particular three kinds of problems can be encountered:

- Deformations of the soil, due to its intrinsic characteristic or due to the solidity (and strength) of the tower, are linear. The result is the leaning of the tower. The most famous case is the Leaning Tower of Pisa.
- Deformations of the soil are not uniform and not linear because the structure is not rigid and resistant enough. In this case we find basically two different situations – although intermediate and combined situations exist – in relation with the distribution of the structure strength:
  - •– Vertical cracks separate the tower – or the structure in general – from bottom to top, into two or more portions which can lean outward (for example the Pre Rup lower south-east tower). This happens when non-uniform soil deformations have a downward

curvature and the structural strength is very low.

- Cracks, deformations, breaking of lintels, etc., mainly concentrated in the lower-intermediate part of a tower. This happens when the stresses on the structure induced by soil deformations in the structure decrease with the distance from the bottom, and in particular when the curvature of the soil deformation is upward.

In arched or vaulted structures, movements of the foundations and outward rotations in particular produce slippage between the blocks in the joints, open up cracks and change the geometry, reducing the contact between the blocks that is limited and concentrated in the corners. It can lead to local crushing phenomena and eventually collapse.

Often, when the building is close to a retaining wall or a canal, an inclination to that side may be produced. On sandy soil, the sand can flow out from gaps in the stones, increasing the phenomenon.

When soil movements are suspected, a monitoring system can be very useful. Continuous monitoring of the inclination of the walls of Prasat Suor Prat N1 tower revealed that the inclination increased suddenly by about 200 mm/24 h after a heavy rain in October 1997. The movement of the inclination was of a cyclic nature before this event.

VIII. Criteria and Techniques for Strengthening Structures

VIII.1. General Criteria

As far as possible the original construction techniques must be respected, though these must be compatible with the safety conditions of the structure and of the foundations. One of the paramount factors in determining the intervention criteria is the type of deformation, cracks that the structure has suffered and, in particular, whether these deformations are now stable in time.

If the deformations are stable, it is necessary to check whether these have compromised the stability of the building and, if so, whether stability can be re-established through specific measures (chains, dowels, grouting, stirrups, etc.).

Various systems may be considered in order to recover the deformations. Special attention must be paid to induced stresses in order to prevent any possible damage. Interventions should not be visible; if this is impossible, the aesthetic impact on the monument has to be carefully assessed before making a final decision.

Leaving a site as an archaeological ruin, with all the traces of history, is a possible choice that should be carefully evaluated in relation with the environment.

The technique of dismantling/reassembling badly deformed or endangered structures can be accepted only after having analysed and ascertained the need and feasibility, and having assessed the risk of altering the authenticity of the monument. Moreover, the trauma to which the building and its constituent materials have been subjected to should be carefully evaluated and considered.

When it is decided to proceed with the dismantling/reassembly approach, great care must be taken to preserve the integrity of the materials. All information concerning the present situation must be recorded (axis lines, stone layers, levelling points, etc.).

Anastylosis is not to be confused with the technique of dismantling/reassembly, even though both approaches have some common aspects. Anastylosis consists of putting back to their original place stones or fragments that have fallen down or been removed at a previous time; in some circumstances, new pieces of stone are used as well.

VIII.2. Choice of Measures to be Undertaken

In order to understand the real risks and decide upon the measures to be undertaken, it is first necessary to interpret the visible signs on the structure. These signs are the following:

- Limited cracks that in dry stone buildings mainly follow a pattern defined by the slippage between blocks. This usually does not reflect a serious situation and strengthening is not required.

- Large cracks can influence the shape of the building, creating deformations, in particular, leaning and outward movements of the facades.

  The structure can then become disconnected and weakened with the risk of the situation worsening in case of ongoing decay processes. Tie bars, chains, anchorages, etc. can be appropriate measures to remedy these problems. In some cases, in order to make such bars invisible, they can be inserted inside holes drilled in the masonry or inside the stones.

  In some cases tie bars, chains and the like can be pre-stressed in order to become immediately active, producing favourable forces or reduction of the deformations. As concerns the materials, stainless steel, which is corrosion-resistant, is the most commonly used; new synthetic materials, as carbon or aramidic fibres are interesting alternatives, especially due to their durability.

- Large deformations, associated with major slippage of the stones in dry block structures, may create supplementary forces due to the change of geometry. When the stones have moved outward, the support may become insufficient.

  These situations may be dangerous and a system of chains may become insufficient. At this point, there are two possible approaches: dismantling and reassembly (paragraph VIII.3) or recovering deformations (paragraph VIII.4).

- Far-reaching movements, such as the inclination of a tower, may create certain risks (toppling over), even if the structure itself does not present significant damage. In these cases, the first action is to monitor and see if the situation has stabilized or not. (See paragraph VIII.5.) Then, the additional forces created by the eccentricity of the dead load have to be evaluated and a check made to see if the stability requirements are satisfied.

  When interventions are needed, the criteria in paragraph VIII.5 can be followed.

- Arches and vaults (which take the form of a tower in Khmer architecture) built with dry blocks present specific problems due to the horizontal joints construction technique. The movement of the blocks not only involves slippage, but there is also alteration of the support. In fact, the horizontal plan of contact between two blocks can be reduced to a limited area, close to a corner, while on the other corner contact has been lost. The whole structure becomes “disarticulated” and its overall strength is reduced with the concentration of forces on the corners. This creates high stresses which facilitate local cracks (crushing) and progressive deterioration. The cause of this phenomenon is usually related to outward movements of the pillars or of the walls where the arch or vault stands.

The measures to be undertaken can be chosen in relation to the following aspects: If the detachments do not involve a large area and there are no signs of damage to the block, the situation can be maintained as it is (or improved with some local anchorage, with bars connecting some blocks and so on). Monitoring needs to be set up if significant changes occur in the future.

In cases where the movements worsen and threaten the equilibrium of the structure, two options are available: Dismantle and rebuild following the recommendations provided in the next paragraph, or recover part of the deformations in order to revert to a more stable situation. Usually a series of jacks are used, firstly pushing up the arch or vault, then horizontally pushing inward the pillars or walls. (See paragraph VIII.4.)

- Retaining structures and walls are frequent in Angkor monuments, given the importance of the function played by galleries in mountain temples. Depending on each condition, measures include load reduction, improvement of the soil's internal friction, enlargement of the area subject to slipping, putting in an effective drainage system or confining the earth mass.

  In the case of collapsing embankments, two main objectives are to be targeted within the project criteria. First, increase the strength capacity of the soil by increasing the in situ density of the soil on which the internal friction angle value strictly depends. The second aim is to improve drainage conditions in the body of earth in order to prevent the formation of residual excessive pore pressure, as compared to the water level outside the embankment. This can be easily realised with the creation of slurry trenches of coarser soil, communicating with the moat or dyke and providing an adequate drainage system for ground surface water. The use of synthetic materials such as geosynthetic fibre can also be encouraged in order to facilitate achieving of both objectives.

VIII.3. Dismantling and Reassembly

Sometimes it is necessary to rebuild part of a structure to guarantee its stability, improve conservation (waterproofing, etc.) or reinsert lost members of the architecture. However, as far as possible, reconstruction should be limited.

When rebuilding is necessary, the techniques and new materials must be compatible and should follow the same geometry and shape as the original, leaving some evidence that makes the new distinct from the old, at least to experts. In special cases, less visible insertions can be done; if this is necessary the intervention should be accompanied by a detailed graphic and photographic documentation of the newly inserted areas.

When the original geometry and shape are not known, the form of the new members should be as simple and inconspicuous as possible, in order to interfere as little as possible with the original structures and not lead to any arbitrary interpretation.

In dry stone structures, besides strengthening measures, it is often necessary to replace blocks that have fallen down. In this case, apart from the case of dismantling and reassembling the whole structure, various kinds of problems can emerge:

- Often blocks key to the stability of the monument cannot be found; if such missing blocks are not too numerous, some new blocks, carved to imitate the originals, can be used.

- When the surviving structural elements, mainly walls and pillars, are deformed, so that fallen or new blocks cannot be replaced correctly, blocks with altered geometry have to be used. When possible, every attempt should be made to recover part of the deformations. The systems used for this should be very carefully evaluated and tested and there should be no risk of damage caused by cracking or flushing to the constituent blocks.

- Issues involving the selection of stone quarries and extraction need to be resolved. New stones must be physically, geometrically and architecturally compatible with the original structure.

- The level of finishing of new stones depends on the specificity of the situation. When there is no reliable information on the decorations available, only the geometry should be reproduced.

- Details can be approximately reproduced only when there is full knowledge of the originals.

- Figurine elements that are part of an iconographic context should not be reproduced when there is a danger of falsification and of a subjective interpretation of the new carved stone that could differ from that of the original which has been lost and is therefore unknown.

- When new stones have to be inserted in a context where the adjacent stone is severely decayed, a delicate aesthetical problem arises. The solution must take into account the general harmony of the area that is being treated.

- The re-use of broken stones usually means that the detached parts must be bonded with adhesives and often strengthened with dowels. It is often necessary to integrate the original stone blocks with new ones. These must be of the same nature and appearance as the original ones. Insertion of new blocks should be limited to the part where blocks are missing when they are indispensable for the stability and necessary for full legibility of the monument.

VIII.4. Recovering Deformations

Recovering deformations is a relatively new technique developed in relation with the availability of more sophisticated tools (jacks, etc.) and the computerised monitoring system always necessary during the work.

The overall project and the programme for the different operations must be carefully prepared, taking the following points into consideration:

1). **Equipment:**
The equipment consists of tools (hydraulic jacks, etc.) to give compression or tension to the structure, and manual or electric pumps. These are connected to the jacks through an oleodynamic system, complete with manifold, multi-way full analogue and digital gauges. Manometers allow measurement of the value of the pressure on the jacks at any time. It is necessary to set up a monitoring system able to measure the stresses on the structure and any movement (inclinations, etc.) or deformation imposed on the structure.

2). **Preparation of the structure:**
Preparation of the structure is divided into two main activities:

- Case-by-case positioning of the jacks, where forces are applied to the structure. A preliminary analysis must be performed to evaluate these forces in relation to the deformation that it is hoped to recover.

- Individuation of the part of the structure that is expected to move and of the lines (usually cracks) where the relative movements are produced. In the case of cracks the width of which needs to be reduced, it is necessary to remove the debris accumulated and anything that could block the movements.

3). Phases to recover deformations:

Usually it is possible to recover only part of the movements or deformations because they are often of an inelastic, irreversible nature. To facilitate the operation, some cuts or discontinuities could be produced artificially.

The pressure on the jacks is gradually increased. Usually different values are assigned to each jack, set up on the basis of previous analyses, in order to limit any additional stresses during this phase.

At each step, the monitoring system has to record pressures and displacements and compare them with the pre-set values. It is not easy to theoretically set the rate between pressure and displacements due to the uncertainty of the mechanism that will be produced and the actual stiffness of the damaged structure.

For this reason, usually during the first steps, the rate between pressures and deformations is measured as a basis to recalibrate the theoretical model. The monitoring system warns if any excessive stress is produced in any part of the structure with a risk of producing new damage.

4). **The final intervention:**
On the basis of the results, and in particular of the percentage of the deformations recovered, an assessment must be made to determine whether further measures are necessary. Usually, these are not required, except for elimination of the cause of the damage if it still exists (for example, tree roots).

Finally, it must be noted that this technique may appear more complicated than it really is. The conservator must have sound experience in its practise, but the results often enable the solving of difficult situations while respecting the historic value of the building.

VIII.5. Structures Affected by Unstable Soil Settlement

Soil settlement is the most important factor affecting structural behaviour in addition to material decay. The problems are often very complex. It is necessary to anticipate the trend of the phenomenon and to evaluate the consequences, as additional stress suffered by the structure would increase leaning, etc. A monitoring system is usually necessary and examination of the recorded data will provide indication on the evolution of the phenomenon.

In general, three options are available:

- Eliminate the cause, i.e. reduce the factor of instability acting on the soil (stabilise the water table) or on the structure (enlarge the foundation base, introduce piles under the present foundations, etc.). These interventions are usually complicated and may create important alterations to the original structure. They may lead to the dismantling of the structure and its reassembly, and may produce irreversible loss of values. Only exceptionally, as in the case of acceleration of the developing phenomena and when there are no other reasonable alternatives, can this approach (technically the most reliable) be followed.

  In the case of leaning, an interesting approach is under-excavation, used to soften the soil in the zone where settlement is not extensive. This is obtained by extracting soil to create cavities under the upstream side of the building. These cavities then close on their own, producing artificial settlement, thus reducing the leaning. This technique was applied in recent years on the Leaning Tower of Pisa to reduce its tilt.

- Eliminate (or reduce) the effects, that is reduce the hyperstaticity of the structure, by creating sliding supports, joints, etc. In this way, the stresses produced by the deformations of the soil may be reduced or eliminated. This option can successfully be applied to complex buildings, but is rarely applied to a monument.

- Increase the strength of the structure up to values sufficient not only to resist the present additional soil-induced stresses, but also to give a new general rigidity and continuity, so as to resist stresses produced by possible future soil settlement. This can be achieved only if the evolution of the phenomenon is slowing down or if, in any case, the corresponding deformations and stresses induced are limited within acceptable values. Possible measures include chains, bolts, tie bars (of stainless steel or synthetic fibres), partial reconstruction of damaged or collapsed parts, etc. These interventions should be associated with a monitoring system in order to control potential future increases and amplifications.

IX. Risk Map

Several monuments are in danger, but the risk of heavy irreversible damage or collapse is not the same in all cases. The urgency of action differs and financial resources are limited, so it is necessary to study case by case the level of risk on each monument or part of a monument and assess the size of the monument, the damage situation and the cost of consolidation works. An order of priorities can thus be established.

The work should be organised using an information input system.

Risk maps and priority lists are prepared when developing a conservation programme. It is necessary to design different risk maps relevant to individual structures (focusing on the macro-problems of stability and collapse of monuments) and to the structural stone, the carvings and decorated surfaces (focusing on conservation problems associated with materials. Risk maps highlight not only damage that has already occurred, but also damage that may take place in the future.

Risks come from weathering, changes in the environment (trees and vegetation), soil settlement, human activities (e.g. tourism), etc.

A detailed survey is often sufficient to isolate the most important risks; in other cases, further investigations and analysis are required.

Usually, there are three risk levels recognised: Zero risk (safe situation), risk one (possible danger), and risk two (unsafe conditions, imminent collapse).

Priority lists are based on the risk maps and encompass other factors, such as the intrinsic value of each monument and the cost of the operations necessary to reduce or eliminate the risks. Priorities are therefore singled out on a cost-benefit basis, where priority is established, taking several factors into account: the extent of the risk and its consequences if left unattended, the cost to remedy it related to the intrinsic value and importance of the monument.

The list of priorities should also indicate how quickly the appropriate measures should be implemented, usually at one of the following three levels:

a). **Emergency (or rescue) measures:** These measures, often provisional, are required when the structure presents a high risk of collapse, and must be taken without delay. These measures are usually removed at a later point or in any case reviewed and replaced by permanent measures. Typical emergency measures are propping, provisional chains, etc.

Due to their characteristics, emergency measures cannot always be carried out within the broader framework of a conservation and consolidation programme. Being temporary, a strict deadline should be defined that establishes clearly when and how the full conservation intervention will begin. Emergency reinforcements should be reversible.

When possible, it is preferable to undertake interventions that are a first phase of permanent consolidation operation.

The materials that are used for the emergency consolidation should not in any way alter the structure during the period that they are in use.

There should be regular monitoring of the emergency consolidation system to ensure that no damage or alteration of any type has been incurred.

When there is no choice but to use materials subject to decay, the monitoring campaign should be carried out more frequently to ensure that the systems remain effective and have not moved or decayed.

If wood must be used it should be treated so as to avoid insect and fungal attack.

The planning and implementation of emergency measures is an extremely delicate phase and experts must be present at all times during these operations to ensure that no risks for the workers and no damage to the structures occur during the assembly and application of the measures.

There should always be full graphic and photographic documentation of any emergency consolidation.

b). Urgent measures: These measures are to be taken as soon as possible, however, sufficient time should be allocated to thoroughly analyse the structure. Therefore, they are the result of a study and are usually a preliminary part of a final intervention.

c). Preventive measures: These measures involve situations where the structure itself is not immediately at risk but may be in danger in the future, especially if certain phenomena are present, such as a tower close to a retaining wall that shows signs of possible movement. Preventive measures are the best policy for the safeguarding of architectural heritage. Maintenance is often the cheapest and most efficient way to achieve this, albeit not always completely sufficient.

As noted above, different risk and priority maps should be prepared for different kinds of structures and/or materials and the interventions to be undertaken, as is the case for the conservation of stone and decorated surfaces. Risks may be produced by infiltration, capillary uptake of water, biological layers, plant growth up on the structure, salt efflorescence, damage resulting from visitors, and so on. The risk map must be seen as a living and ongoing element within the framework of a conservation institution. When a conservation intervention is completed, the risk map must be updated in order to reflect this change.

X. Closing Remarks and Acknowledgments by APSARA–UNESCO

This charter clearly recognises the great importance of on-going research and the consequent evolution of conservation methods and materials. Its drafting began ten years ago (2002) by an interdisciplinary group of conservation professionals who have been involved continuously in the field of heritage conservation and for the last 20 years specifically in the complex issues of safeguarding Angkor.

We wish to deeply thank the working group under the chairmanship of Professor Giorgio Croci. The dedication of these men and women to the cause of Angkor has been a defining factor in this charter which reflects many years of expertise in the field. The recommendations have no other ambition than to serve as guidelines for the present and future generations of heritage professionals.

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