Geotechnical Study on Ground and Masonry Structures in Angkor for Safeguarding Monuments

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Abstract

This paper presents the results of geotechnical aspects of preservation of Angkor monuments in Cambodia through the activity of the author as the head of the Geotechnical unit of Japanese Government Safeguarding Team for Angkor (JSA) since 1994 (Team head: Dr.Takeshi Nakagawa, Professor of Architectural History at Waseda University). JSA is an organization based upon the request of Royal Government of Cambodia in 1994 through UNESCO/Japanese Trust Fund for the Preservation of the World Cultural Heritage.

Geotechnical Characteristics of Angkor:

The paper reviews metrological, geological, and geotechnical studies in the past that includes map of general geology of Cambodia and some specific study in Angkor region. The author further deepened the geological study through carrying out several geological boring to reach base rock. The paper clarifies that the surface geology is lateritic nature of sandy silt of brown and yellow in color and about 40m in depth with averaged blow number of Standard Penetration Test as N=20.

Top surface of 4-5m from the surface is found strongly affected by seasonal change of water table. More than 1000 pumping well were surveyed and recent trend of lowering under ground table is anticipated, which may result in differential settlements of the monuments.

Among many monuments in Angkor, the author studied three problems of stability of Prasat Suor Prat and Central Tower of Bayon Temple, and preserving work of North Library, Bayon Temple. Generally, visual observation was made before instrumented monitoring was performed. Measurements of structural behavior and ground movements with underground water have been made as well as weather records of rainfall, wind, and temperatures.

Some conclusions on three sites are as follows,

Stability of *Prasat Suor Prat*: *Prasat Suor Prat*, which means "tower of rope-dancer," is twelve independent masonry towers made of laterite block with two ponds. Powers near the ponds are found inclined towards ponds. The foundations of the Towers near the ponds are also found expanded horizontally. The embankment of the south pond has been displaced towards pond near the tower called S1. The load of the tower near embankment has caused an inclination and spreading of the ground behind the embankment.

Stress concentration caused by vault system without wedge arch resulted in failure of laterite foundation blocks. Monitoring showed that heavy rain had triggered a long term inclination of the Tower.

Stability of Central Tower of the Bayon Temple, Angkor Thom:

The Central Tower is massive stone masonry tower and lacks symmetry, which is expected at the original shape, and the mode of collapse is anticipated by not the total overturn like Pisa Tower but falling out of pieces of stone blocks.

Gap sensors were used to monitor the opening between blocks of stones. Daily gap change is to close during daytime and to open in night, which was confirmed as temperature effect.

In addition to the daily changes, sudden changes were also recorded These sudden changes take place when strong wind blows. The author found special tension cracks on stone surface, which was caused by horizontal displacement of adjacent column. This tension crack may be accelerated to develop resulting complete falling off from the Tower.

These above-mentioned conclusions were only possible through observation of monitoring system of frequent sampling; say one sample per hour, with precise sensors.

Preserving work of North Library, Bayon Temple:

Library is an independent structure that consists of filled foundation and upper structure. The main feature of project in terms of geotechnical engineering was to dismantle the side portion of the filled foundation and reconstruct the embankment. Due to high embankment of about 5m and necessary bearing capacity, slacked mixed soil was compacted to make the foundation.

The author likes to suggest that man made fill with steep slope is of great interest in geotechnical engineering and the decay of laterite block is one of major cause to results in structural failure of the monuments stresses needs of further study.

1 Preface

In 1993, an international inter-governmental conference on Angkor was held in Tokyo by UNESCO to call upon the safeguarding and development of the historical area of Angkor. Being requested by Cambodian government, Japanese government team of safeguarding Angkor (Team leader: Dr.T.Nakagawa, Professor of Architectural History, Waseda University) was organized in November 1994 through UNESCO/Japanese Trust Fund for the Preservation of the World Cultural Heritage.

The author was asked to study geotechnical problem in Angkor. The author had joined the team and stayed in Angkor several times a year since the beginning. The first phase of the activity was ended in 2000. This study is a summary of the geotechnical engineering view in this period.
In 1975, I had a chance to work geotechnical aspects of safeguarding the monument of *Borobudur* in Indonesia, where the Monument had been taken cared by UNESCO. I was acquainted with late Dr.Daigoro Chihara at the site and it was he who recommended me to work Angkor monument in geotechnical engineering. Dr.Chihara told me the Angkor had been reached high cultural states by developing water usage and stone handling. From the beginning of 1994 of my first visit to present, I met with not only various geotechnical problems but also many people including Khmer, French, Italy, China, and German to discuss the problems. Since the first period of JSA had ended in 2000, I began to compile the results of geotechnical study.

2 Introduction

2.1 Cambodia and Angkor

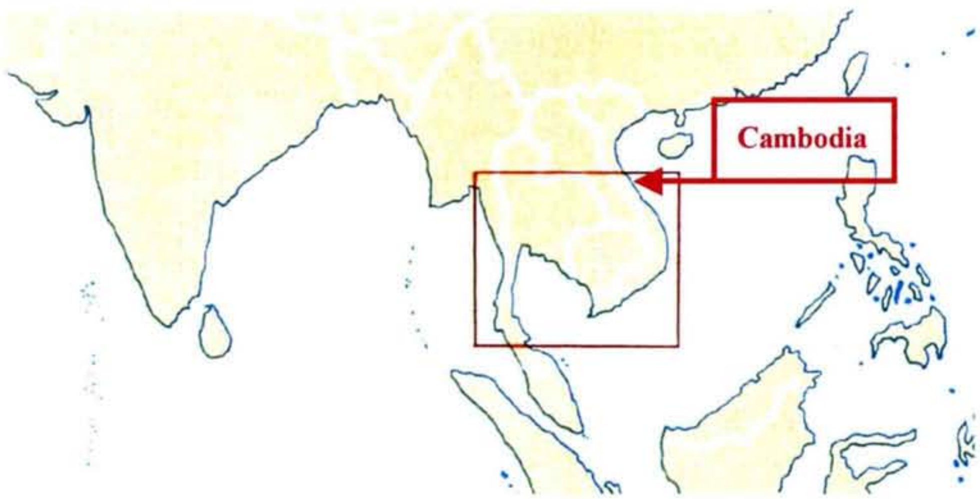

Fig.2-1 Location of Cambodia

Cambodia locates in the southern end of Indonesian Peninsula as shown in Fig.2-1 and Fig.2-2. The river Mekong, which originates at the mountain range in China and flows south in the countries of Laos, along with the boundary between Thai and Laos, comes into Cambodia and Vietnam, and flows out at around Saigon (presently, Ho Chi Minh city) to South China Sea.

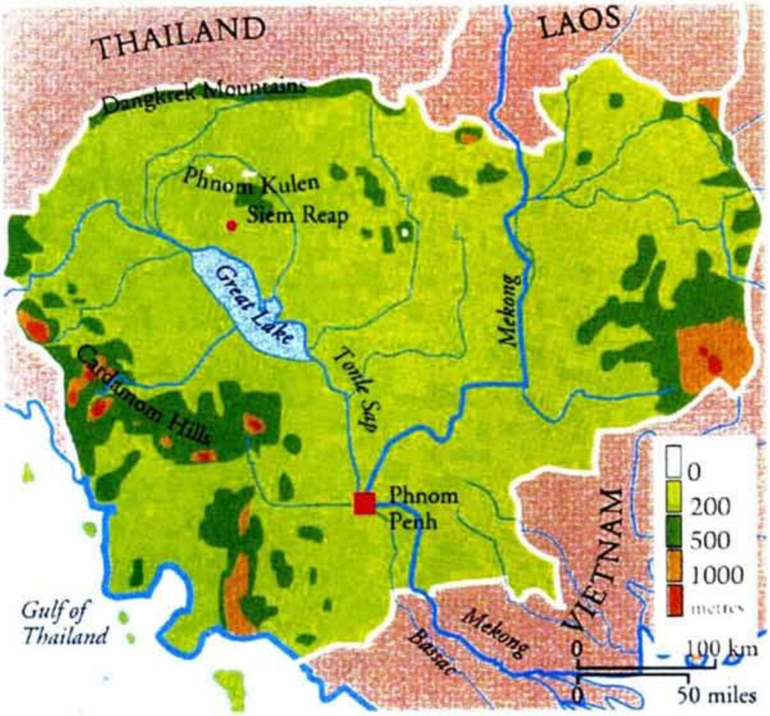

Fig.2-2 Map of Cambodia

A lake known as Tonle Sap (large great lake in Khmer language) lies in the western side of Cambodia has its area of about 1,000km^2.The maximum depth of the Tonle Sap is about 14m and average depth is very shallow of about 3m. The Tonle Sap Lake is connected by Tonle Sap River with the Mekong River at Phnon Penh, the capital city of Cambodia. Water of the lake flows out into the Mekong River in dry season. However, when rainy season comes, the water level of the Mekong River rises up about 8m, which causes reverse stream back to the Tonle Sap Lake from the Mekong River.

The lake widens its area three times in rainy season larger than in dry season. The shoreline of the lake is flooded every year in rainy season. Small bushes and grasses grow near he shore line in dry season become under water during rainy season. These seasonal cycles of nature under the constant high temperature of about 30°C results in feeding not only fertile resource to the agriculture but also food for fish in the lake.

Khmer is the name of the people who speaks Khmer language and lives in the southern portion of the Peninsula. The Khmer has its brilliant history back to 1,000 years. It was in A.D.802 when a young King, who was known as *Jayavarman II* and had been captured in Indonesia and returned to Cambodia, declared the independence of the Khmer country on *Mt.Phnon Kuhlen*, north of the Tonle Sap Lake. Angkor, which means "royal city" from Sanskrit "*nagara*", locates wide area of 20x20km^2 near the present city Siem Reap.

Angkor is also the name given to the Khmer dynasty. The first establishment of the Angkor Empire (A.D. 802) and continued to its abandonment of Angkor due to the Siamese invasion in 1434. The historical structures could be found about 600, among them the famous ones are Angkor Wat(early 12 century) and Angkor Thom(late 12 century). These historical facts are understood by reading inscriptions of many stone monuments erected in the area.

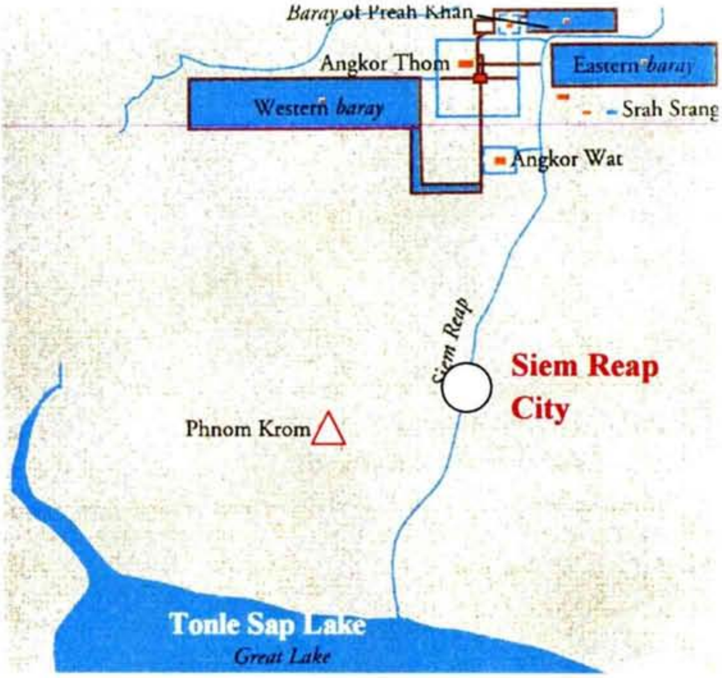

Fig.2-3 Siem Reap city and Angkor

Khmer Empire has left various great monuments in civil works. Among them, there are several man made lake, called as "*baray*" as shown in Fig.2-3. The Western baray (length of EW direction 7km, width of NS direction 2.5km) is still used for irrigation of rice field in the area as well as to feed water to the moat of Angkor Wat. Construction of barays enabled to live under the dry season without rain.

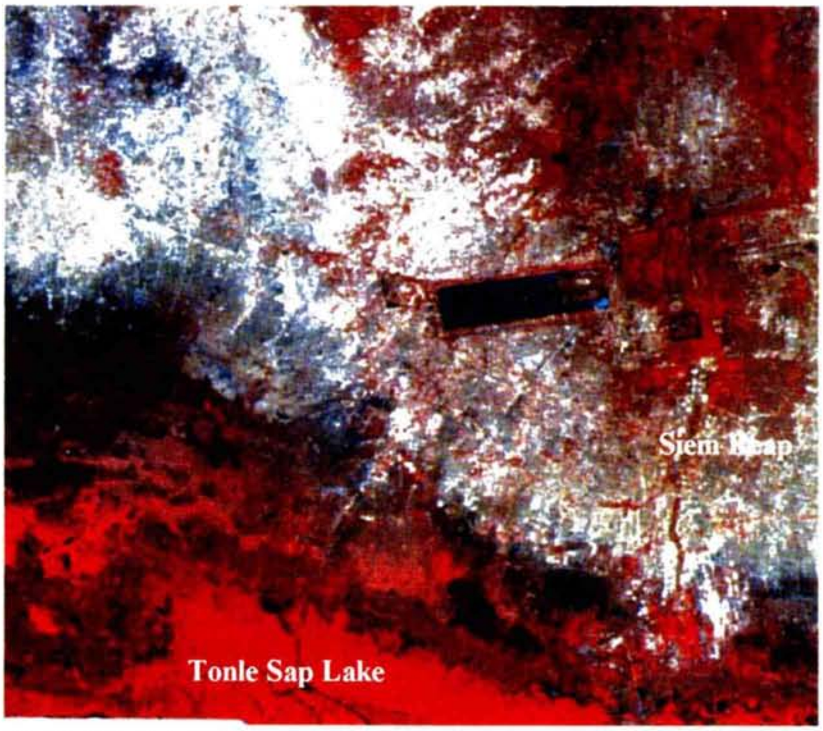

Fig.2-4 Satellite image of Angkor

Fig.2-4 shows Angkor image from the space.
The lower red portion is the Tonle Sap Lake. The Angkor Wat, Angkor Thom, West Baray, and East Baray are easily recognized.

2.2 Historical Review of Safeguarding Angkor1 References

Angkor is the name given to the Khmer dynasty from its establishment of the country in 802 to its

abandonment of Angkor due to the Siamese invasion in 1434. The historical structures could be found about 600, among them the famous ones are Angkor Wat (early 12 century) and Angkor Thom(late 12 century).
Most of these monuments are found surrounded by a moat. A tall tower stands in the center of the monument, which is considered as to symbolize Mt.Mehr where Gods stays. The moat is also considered as a symbol of ocean.
After the discovery of Angkor by a French naturalist Henri Mouhot in 1860, Angkor was well known to western world. French made a great contribution of preservation and research work by EFEO(Ecole Francaise d'Extreme-Orient) from 1908 until 1970 when the Pol Pot invaded Angkor area. According to UNESCO, the work by EFEO is classified into three stages(UNESCO(1993-1)).

2.2.1 1st Stage(Clearance and Emergency Consolidation Works)

1908-1931 Clearance work in the major sites including Angkor Wat, Angkor Thom, Preah khan, and Ta Prohm. Shoring and strutting of fragile monuments were carried out.

2.2.2 2nd Stage(Introduction of Anastolosis) 1931-1959

EFEO introduced a new concept of safeguarding structures as "*Anastylosis*", which is a Greek work (*anasto + lo + sis*) put it back in order, after learning from the restoration work at Borobudur, Indonesia. Anastolosis is to collect scattered parts, identify the right position of missing elements, and put them back to the original position.

2.2.3 3rd Stage (The Establishment of Angkor Conservation Office) 1960-1970

EFEO established the Angkor Conservation Office in Siem Reap in 1960. A thousand workers became to be employed for restoration and maintenance. More than 100 specialists of scientists and conservators were engaged for safeguarding works.

2.2.4 Pol Pot Regime

June 6, 1970 Pol Pot invaded Angkor region and the conservation works became difficult to be carried out. It was until 1989 when the UNESCO was allowed to visit the site after the political fractions had reached to negotiate to keep peace.
In 1990 and 1991 UNESCO had organized international meetings of professional conservators on Angkor monuments. In 1993, the first international inter-governmental conference was held in Tokyo to discuss the outline of cooperation of safeguarding the site.
In 1992, the Angkor was approved and registered as World heritage by UNESCO.

2.2.5 International Cooperation of safeguarding of Angkor

Before 1993, several such countries of India, Poland, U.K., and Sweden other than France had contributed not only conservation of monuments but also regional development project.

After 1993, France had completed the restoration of Terrace of King Leper and continued working on Baphuon. Indonesia had completed several gates of the Palace of Angkor Thom. German group has been studying chemical weathering of sand stone relief at Angkor Wat. Italian team made restoration work on Pre Rup. Chinese team began their study on Chau Say Tevoda.

2.3.1 Review of conservation method for Angkor Monuments

The preservation efforts were made early in 1900 by French people by EFEO(Ecole Francaise dExrteme-Orient). From 1908 to 1931, clearance work at Angkor Wat and Bayon and consolidation of damaged structures were made.

Structures in danger of collapse were propped and cracks were filled with mortar made of gravel, sand, and mud. The clearance was extended to include canals, Royal Plaza, footpath, and road. In 1925, Angkor Historic Park was officially declared and maintained until 1970s.

In 1929, a Dutch architect, Dr.Van Stein-Callenfiels, visiting Angkor invited French to see his reservation work on Borobudur, Indonesia. The mission returned from the Indonesia, French began in 1931 a new method of conservation known as "Dutch's method" or "Anastolosis."

"*Anastolosis*" is internationally recognized as a standard method to be applied restoration work of historical heritage, which JSA also recognizes basic principle to restore Angkor monuments.

"*Anastolosis*" is a Greek that combines "*Ana*(re-establish or going back in time) + *stylos*(column)+*is*(a suffix to make noun)".

Photo 2-1 *Banteai Srei* from air

"*Banteai Srei*", which means "the citadel of woman", stands on a foot hill at southern edge of Mt.Phnon Kelen. Small scaled made of red-yellow stone is an unique beauty in Angkor.

Photo 2-2 *Devada* (Goddess) at Banteai Srei

Based upon *Balanos* of Architect in Greek who expounded the theory of *Anastolosis*. *Anastolosis* consists in the restoration or re-erection of a monument using its own materials and according to the construction methods proper to it. *Anastolosis* allows the discreet use, where justified, of new materials to replace missing stones in the absence of which it would be impossible to replace the old component. The Dutch was the first to introduce this method in Asia to restore the Borobudur monuments in Indonesia from 1907 to 1911.

2.3.2 Application of Anastolosis to Angkor Monument

The technique was introduced into Angkor and a monument called "Banteai Srey" was restored by the method of "Anastolosis" in 1930's.

Based upon *Anastolosis*, two major steps have been followed as follows.

1. Cleaning, excavation and plan, search for stones, first attempt at reassembly by lying out on the ground, dismantling of standing sections course by course.
2. Hardening of the ground (with or without a concrete platforms), reassembly with insertion of new stones where necessary (these new components are not sculpted, but roughly hewn, and identified by lead markings) and without using mortar for the facing (the stones to be held in place from behind by iron cramps).

2.2.3 Modification of Anastolosis to Angkor Monument

Though the theory of anastolosis is considered good to keep the authenticity of the original monuments as long as possible, it was realized by a French conservator, B.P.Groslier, that there is a poor condition not to be able to support the loads required to bear.

The sandstones or laterite blocks, if degraded, only putting them back to the original position results in structural failure. To avoid such disasters, it is necessary to add some internal reinforcement or protective measures to counteract mechanical degradation of the structures.

French team had developed and added a new concept to the traditional anastolosis when they began to restore "*Baphuon*". One of the big problems was how to make the very steep slope of the filled mound. The temple was built upon a man made mound with base length of 107mx132m.

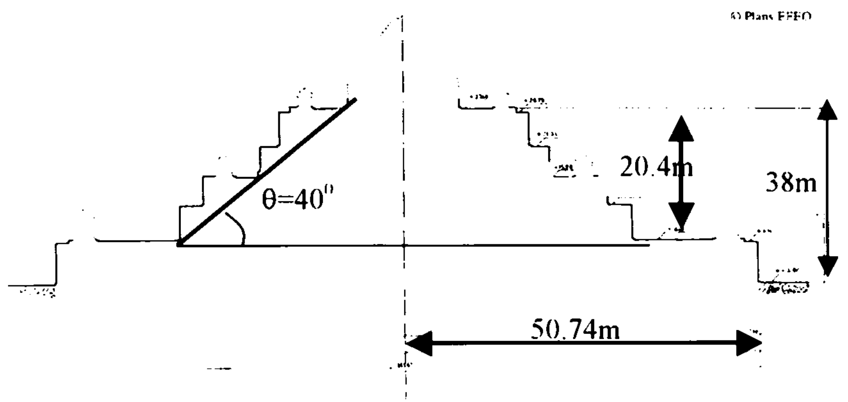

Fig.2-5 Section of *Baphuon*, Angkor Thom

The slope is very steep of 40 degree with more than 20m in height as shown in Fig.4-1. In 1950', they had attempted to restore the steep slope hill by filling up soils, however, the slope failed when the height became about 5m. They tried the filling again, the slope failed again.(B.Dagens,1989, Paskal,1987)

Finally, the French abandoned the anastolosis method of original embankment of filling the mound with only sand. They have modified the method introducing reinforced concrete retaining wall inside the slope surface to protect the slope failure.

Fig.8-31 and 8-32 show concrete retaining wall behind the slope surface of decorative sandstones.

Photo 2-3 Steep embankment slope with concrete retaining structure

Photo 2-4 Crack appeared on top of the filling slope (photographed in October, 1997)

In September 1997, it was a heavy rain of about 200mm in one day, which caused not only a failure of embankment along the moat near the causeway to Angkor Wat but also resulted in horizontal crack of about 20m in length around top of the filling hill of Bapuhon. Fortunately, the width of the crack did not increase and the slope did not failed.

It should be realized that the '*anastolosis*' may not be applicable for some cases and is necessary to modify or even to include modern technology to keep up with the present and future conditions of monuments itself as well as surrounding environments.

2.4 Conclusion

In this chapter, the author tried to review geotechnical aspect of the consolidation technique of the monuments of Angkor in the past.

France had devoted in the conservation of Angkor monument since the beginning of 1900. Pol Pot invaded the Angkor in 1970 and no work has been progressed about 10 years since then. UNESCO took an initiative for safeguarding the monuments and had organized international cooperation. Presently, several groups from different countries have joined the activities since 1993.

"*Anastolosis*" is the way to be followed during conservation of cultural heritage. Anastolosis insists to use "original material" by "original method," if otherwise the heritage fails.

If we follow "*Anastolosis*" in handling soils and ground, we shall have some difficulties. The high embankment of about 40m with steep angle of slope of 40 degrees at Baphuon temple is a good example how the ancient Khmer engineer knew some method which resulted in success of Baphuon, which our modern geotechnical engineer do not understand, or could not even estimate. When I made discussion with Mr.Pascal, a French conservator, who told me the history of French team during a process of Baphuon.

We have to make efforts to study how the Khmer people had handled soils and foundations in the process of construction of Angkor.

2.5 References

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3 Topological and Geological Setting

3.1 Topology of Angkor Area

The Angkor plain extends from the north shoreline (GL=+0m) of Tonle Sap Lake to the mountain foot (GL=+50m) of the Mt.Phnon Kulen ("*Phnon*" means mountain in Khmer) as shown in Fig.3-1. The horizontal distance from the shoreline to the mountain foot is about 50km. The average degree of inclination of the slope is rather gentle of 1m/km.

The northern mountain range Phnon Kulen was the old quarry site to have provided the sand stones to construct the temples in Angkor region that locates about 25km from the mountain foot.

It is identified three major topological regions in the Angkor plain, between the Kulen plateau and the Tonle Sap Lake. Ang Chouleang et al. (1996) referred these regions as ancient terraces, young alluvium terraces, and the lacustrine plain.

The ancient terrace corresponds to Battambang formation and the young alluvium terrace and lacustrine plain correspond to Upper and Lower Tonle Sap formation in the Geological Map in Fig.3.2.

3.1.1 Ancient Terraces:

The most of the Angkor monuments were founded on the stable ancient alluvial terraces of about higher level of GL>=+20m. The old Khmer engineer had selected the place with agriculturally arable superficial soils and a sound ground for structures.

The eroded soils from the Mt.Phnon Kulen flows down to the Angkor plain by river and spread over by flood. Coarser material of gravels and sands resists against water flows and stays on the ground surface. Finer materials of silts and clays are more easily flown out further from the mountain to the Tonle Sap Lake.

The main reason of the existence of the different levels of terraces may be due to tectonic movement or the higher level of the Tonle Sap Lake in the past. If this area has been tectonically stable, the latter reason is very much likely. Cyclic nature of glacial age every 40-50,000 years in Quaternary geological period have resulted in worldwide sea level changes of about 100-200m. Under the glacial period of low temperature condition, seawater freezes and concentrates to north and south poles. During the inter-glacial period of warmer condition, the ice of the poles becomes to melt which results in raising the seawater.

If the Angkor region has been tectonically stable and when the sea level becomes lower then that of the previous inter-glacial period results in the higher terrace. Or, if the region is constantly lifted, the rise of the region results in the discontinuous topological feature.

3. 1.2 Lacustrine Plain

The water level of Tonle Sap Lake rises about 8m every rainy season that results in flood near the shorelines of the lake. A shore band of 5-10km in width where the flood takes place annually is the lacustrine plain.

3.1.3 Young Alluvium Terraces:

Between the ancient terraces and the lacustrine plain, young terraces is identified as of alluvial deposits dating from the last glacial era. Northern part of the terraces is supplied eroded soils of the ancient terraces. Nearer to the lake, the young terraces are affected by the annual flooding.

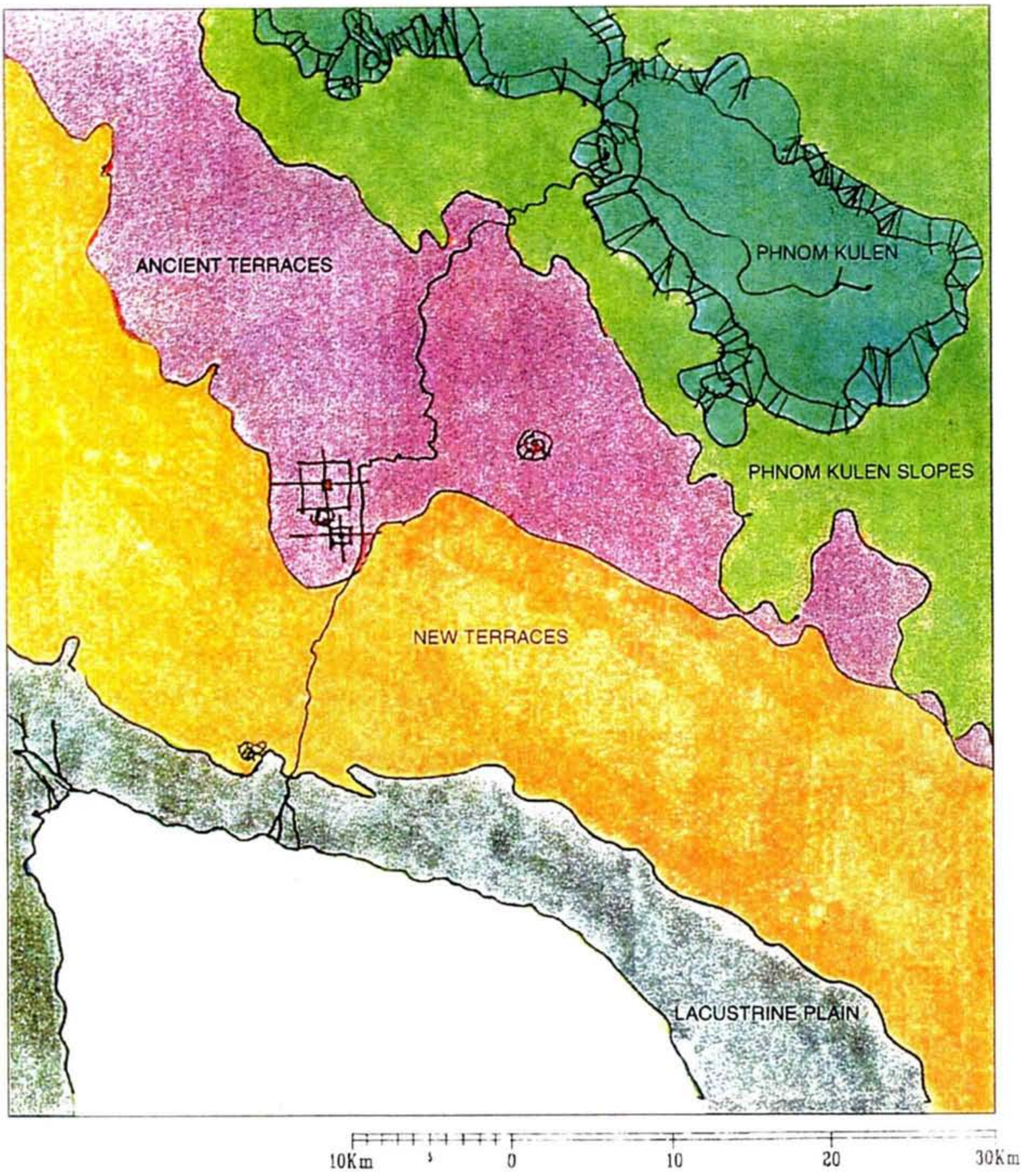

Fig.3-1 Topological Map of Angkor Region (from Ang Chouleang et al. (1996))

3.2 Geology and hydrological study

Geological study in Cambodian region was published as "Geological Map of Cambodia, Laos, and Vietnam (1:100,000)" in 1991 by Vietnamese Geological Survey.
Another map of "Hydro-geological map(1:100,000)"was published by Mekong Committee in 1992. This map was compiled to show distribution of water bearing layers based upon topological features and geological outcropping.

The Endeavour was utilized to take a Synthetic Aperture Radar Image of the Angkor area from space in 1994 and discussed on the possibility of the use of satellite image in a wide range survey (World Monument Fund(1995)).

As discussed later, the surface geology in Angkor area is described as composed of Holocene and Pleistocene deposits with very gentle slope.
Since there had no geotechnical study in the area, JSA made several geological borings of 100m in depth and found a new fact on the base rock in the area. Based upon the study as described later in detail, the base rock was found about 60-80m from the surface. The upper soil layer of 40m in the area consists of yellow and yellow brown clayey silty sand of latesol with SPT N value of about 20.

Dumarcay(1997) discussed hydraulic systems in northern part of the regions based upon archeological evidences.

Recently Moriai (2000) summarized general geology of Angkor area and discussed characteristics of laterite on the monuments.

Dr.Nishimura(1997) reported some preliminary results on electric survey, geo-magnetic survey, and radar survey applied in the area and showed potential applicability and some necessary weather conditions to perform the survey.

Hungary (Angkor Foundation(1993)) made a survey on hydraulic systems of Siem Reap river, which flows nearby the monuments to obtain fundamental data to control water system in the area.

France funded an electro-magnetic survey to locate the old canal channel in Angkor Thom as a preliminary study for archeological investigation (Drs.R.P.Exaltus & Ing.P.J.Orbons(1996)).
Giorgio Croci(1998) visited Angkor monuments as an UNESCO expert and reported on the stability of masonry structures of corbel arch as well as geotechnical problems.

Several works have concentrated to investigate some specific study related with geotechnical problems. However, there have been no systematic studies on geotechnical characteristics in Angkor area before 1994, when Geotechnical Unit of the Japanese Government team began to work in this field.

3.3 Geology of the Angkor Area

Geological study in the past shows that the coastal area of Tonle Sap lake is consist mainly of quaternary sediments with small rocky hills. As shown in Fig.3-1, the Angkor area locates at the middle point in the very gently sloped plain (about 1:1,000), which extends from the shoreline of Tonle Sap to the Mt. Kulen some 40km north of the lake.

Fig.3-2 shows the geological map of Cambodia compiled by Phan Cu Tiem(1991) of Geological Survey of Vietnam.

The surface geology of the Angkor area is quaternary sediments. The map shows several units of different ages and origins.

Table3-1 Quaternary Geology of Angkor Area

Geological Age	Unit	formation	Description
Holocene			
Q_{IV}^{3}	Upper Holocene	Upper Tonle-Sap Q_{IV}^{2-3}	The youngest sedimentary layer +1.5-2.0m near shore of the Lake
Q_{IV}^{2}	Middle Holocene	Lower Tonle-Sap Q_{IV}^{1-2}	Lower terrace +4-5m
Q_{IV}^{1}	Lower Holocene		
Pleistocene			
Q_{III}	Upper Pleistocene	Battambang Q_{II-III}	Middle terrace +10-15m
Q_{II}	Middle Pleistocene		Higher terrace +25m
Q_{I}	Lower Pleistocene		Higher terrace +25m

(After Geology of Cambodia, Laos, and Vietnam(1991), Hanoi)

In the geological map, the geology of coastal area along the Tonle Sap is denoted as QIV2-3 of middle to upper Holocene called as Upper Tonle Sap formation. The Siem Reap area, which locates about 10km north from the lake, is covered by older sediment of Lower Tonle Sap formation denoted as QIV1-2(Lower to Middle Holocene). The C14 analysis in some place is reported to give the age as 4,000 to 7,500 years. The Tonle Sap formation is composed of gray silts, sands containing organic remains, widespread around the lake.

In the area of Angkor ruins, Middle-Upper Pleistocene sediments of QII-III (Battambang formation) become to cover the surface geology.

The region's underlying bedrock is considered largely sedimentary in origin. Limestone beds have been eroded and overlaid by later sandstone. From the Kulen hills to the Tonle Sap lake, a wide plain slopes gently to the south and is covered by sandy alluvial sediments derived in large part from weathering of the sandstone in the hill. Minor sandstone and rhyolite outcrops occur on the plain and a small area of red basalt lies adjacent to the base of the south-western slopes of Phnon Kulen.

Fig.3-2 Geology of Angkor Region (After Geology of Cambodia, Laos, and Vietnam(1991), Hanoi)

a apd. Boulder, pebble, gravel, sand, debris

a a, ap Sand, silt, clay, peat
b Basalt

m, a, am, vm, b, mb, ba (m) abi, ba, Sand, silt, clay, peat *Thaibinh* (1,3), *Cuulong*, *Longxuyen* (7) Formations and *Hue* Suite (5) Sediments of terraces (1.5-2m)

a m, am, bm (v) Sand, silt, clay, peat *Haihung* (1,3), *Haugiang* (7) *Thuathoa* (5) Formations Sediments of terraces (4-5m).

a, m Sand, silt, motley coloured clay *Vinhphuc* (1,2,3,5), *Moduc* (6), *Mochoa* (7) Formations, *Danang* yellow sand (5) Sediments of terraces (10-15m).

a a, am Boulder, pebble, gravel, lateritic sand *Hanoi* (1,2,3,5), *Vientian* (6) *Cuchi* (7) Formations. *Phanthiet* red sand (7), *Battambang* grey soil (7,8).
b Basalt.

J_3-K Upper Jurassic - Cretaceous a Red conglomerate, sandstone, siltstone, claystone : *Champa* Formation (5,6) and others (4,5). Conglomerate, sandstone, lignite and gagate bearing beds in some places : *Phuquoc*, *Cardamon* Formations (8).
b Red sandstone, andesite, dacite, tuffs *Cato* Formation (7) Orthophyre, dacite, tuffs, red siltstone : *Vanchan* Formation (3) and others

T_3 Sandstone, siltstone, shale, marl, coal seams : *Suoibang* (3) *Vanlang* (2) Suites and others (4,5). Conglomerate, sandstone, siltstone, coal seams *Hongai* (1,2), *Nongson*, *Dongdo*, *Namneun* (5) Suites

T_{2-3} Shale, siltstone, sandstone : *Laichau* Formation (3) and basalt, tuffs, limestone in some places *Muongtrai*, *Nammu* and *Songboi* Suites (3).
Red sandstone, siltstone, conglomerate and marl : *Mauson* Suite (1,2).

T_2 a Limestone, marl : *Dongglao* and *Namthum* Suites (3) Limestone, siltstone, sandstone : *Honnghe* Formation (8).
b Rhyolite, dacite, tuffs, siltstone, sandstone, marl, limestone : *Nakhuat* (1,2), *Dongtrau*, *Namsam* and *Quilang* (5) Suites. *Chuklin* (7), *Rovieng* (7) Formations.

T_{1-2} Conglomerate, siltstone, sandstone, shale, rhyolite, dacite, tuffs, limestone *Mangeang* Formation and others (6,7) Conglomerate sandstone, siltstone, shale, limestone, rhyolite, basalt, tuffs *Songhien* Suite (1,2).

T_1 Siltstone, sandstone, shale, calcareous siltstone and sandstone : *Song Saigon* (7), *Langson* (2) Suites, marl, basalt, tuffs in some places *Coma* Suite (3)

Fig.3-3 Legend for Geology of Angkor Region (After Geology of Cambodia, Laos, and Vietnam (1991), Hanoi)

The Middle-Upper Pleistocene formation comprise mainly alluvial grits, pebbles, and sands, which are weathered strongly in the upper part of the Formation and reported to have the thickness of about 200m in Bateman. In Angkor area, no data was available on the thickness of the sediments. As shown in the later section, it is found about 40m of the thickness by geological boring.

3.4 Deep Geological Boring in the Angkor Area

Geotechnical Unit, JSA made a deep boring of 100m in length to obtain the basic knowledge of the regional geology.

Preliminary electric survey was performed to estimate the necessary depth to reach the base rock. However, due to the weak contrast of electric impedance of surface deposits and the base rock outcropped at Phnon Baken, near the Angkor Thom, it was difficult to determine before the drilling precisely except to estimate the sediment thickness more than 50m.

Photo 3-1 The first deep boring at Angkor Wat

We have proceeded the drilling at several sites shown in Fig.3-4 as follows,
Royal Plaza near Prasat Suor Prat,
Bayon temple of Angkor Thom,
North Library, inside of Outer Wall of Angkor Wat, and
Siem Reap city.

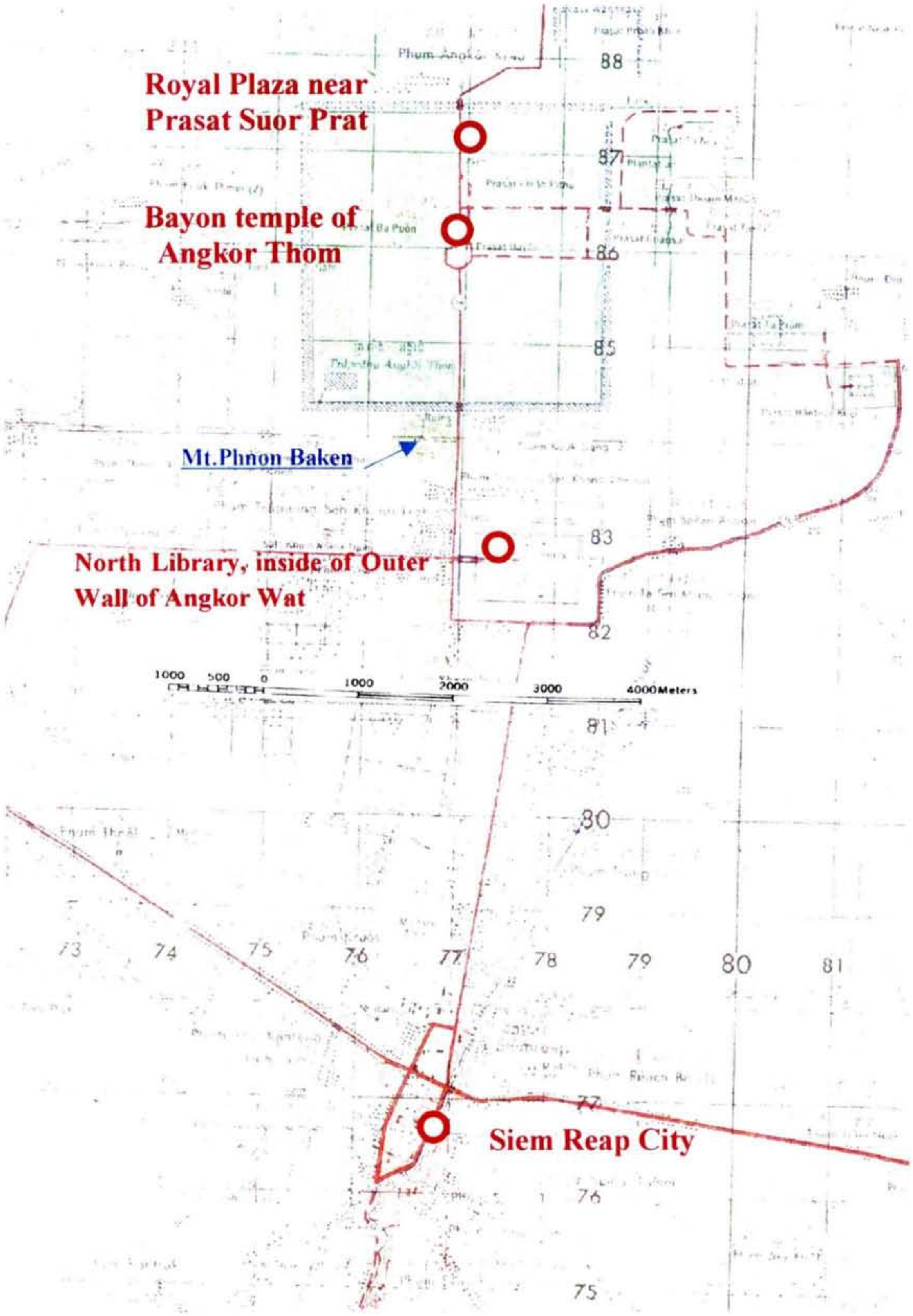

Fig.3-4 Deep Geological Boring Points at Angkor

At every point except the point in Siem Reap, two types of borings were carried out. The first boring was to perform SPT (standard penetration test) for every one meter down to STP greater than N=50. After confirming the hard rock, all sample boring was performed from the ground surface to GL-100m.

Fig.3-5 shows the SPT boring at Bayon Temple, Angkor Thom. The boring was carried out with SPT for every 50cm.

During the drilling, field pumping test s were carried out and permeability of the upper 40m were obtained as an order of k=10^{-3}cm/sec.

As shown in Fig.3-5, the top surface of sandy silt layer is considered as basic water bearing layer in the layer. Water infiltrated from the top surface flows down to Tonle Sap through this layer.

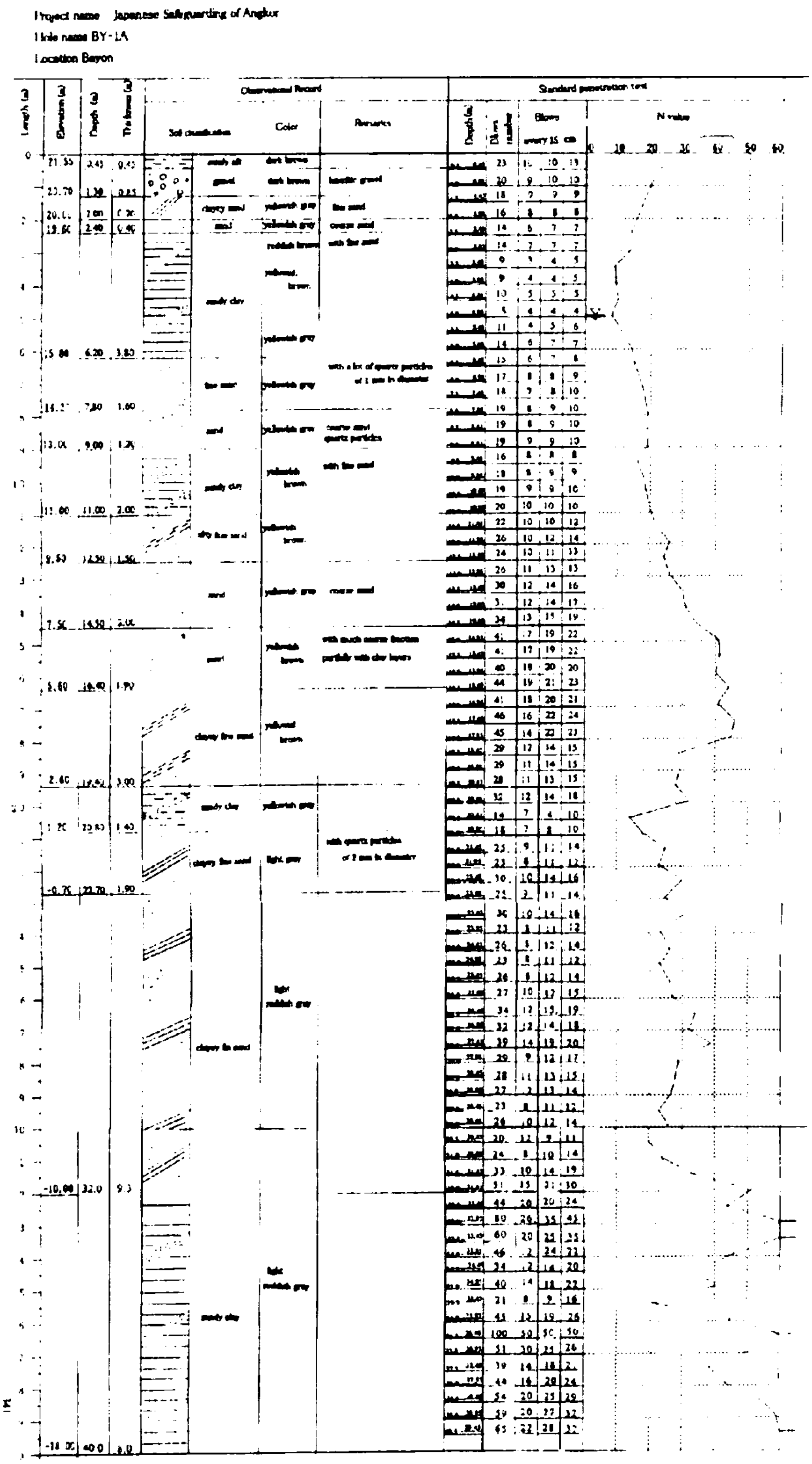

Fig.3-5 SPT Boring Log (BA-1Y) at Bayon Temple, Angkor Thom

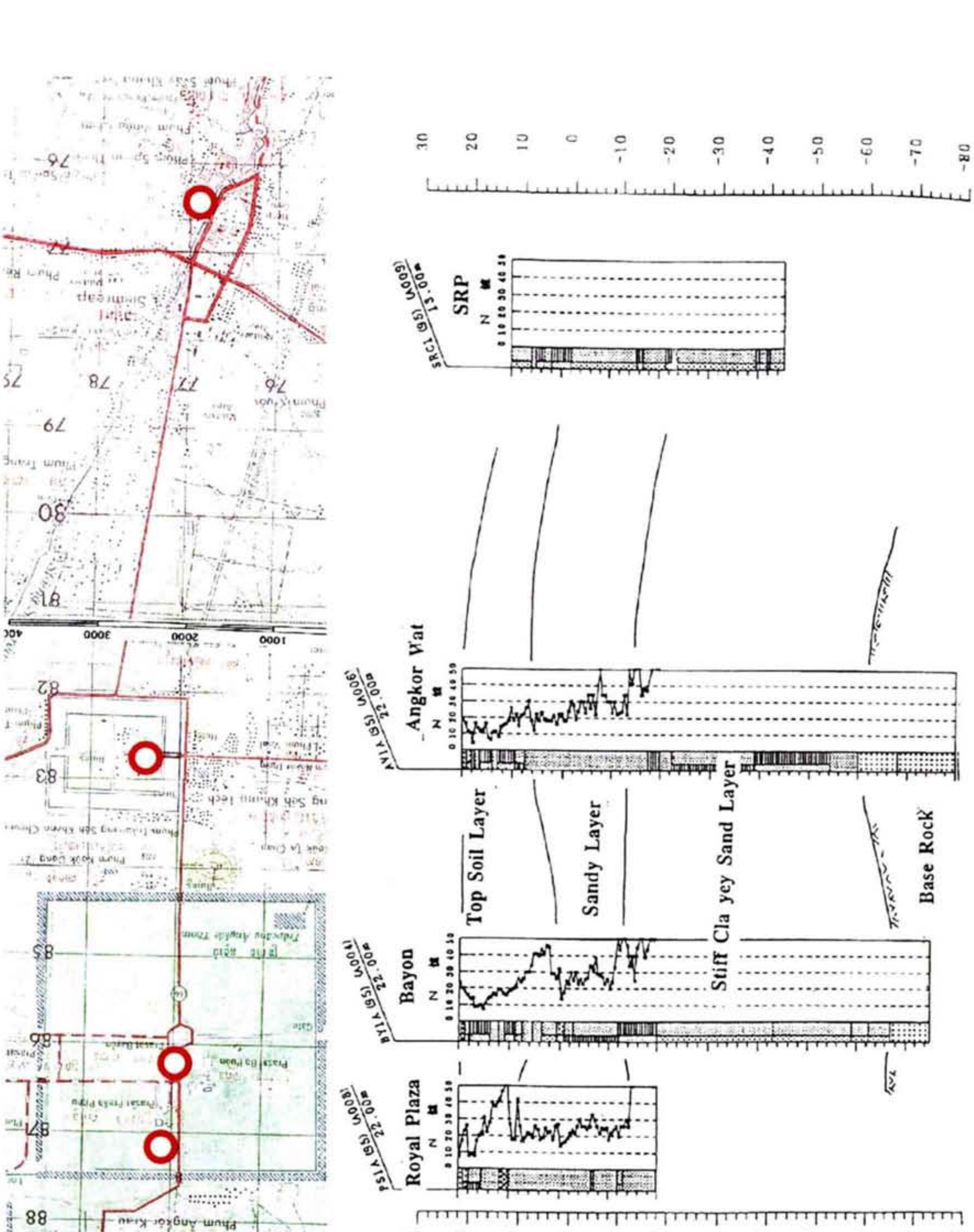

Fig.3-6 North to South Geological Section in Angkor

Five borings to cover the area showed some characteristics of geological formations. The surface geology is lateritic soils with about 40m in thickness and SPT values of N=20 in average with increasing number with depth. The basic rock was found around 80m from the surface.
As shown in Fig.3-6, the surface layers may be divided into two layers according to the characteristics of variation of SPT-N value with depth. There are a few layers that show relatively high N-values.
These relatively high N-value layers are generally sand/gravel rich layer and may be considered as water bearing layers. These layers in the ground play to transmit underground water compared to the silty or clayey impermeable layers. The origin of the mother rock is estimated as the mountain range of Phnon Kulen some 25km north of the area. The sand gravel layer may correspond to sediments during the glacier periods, while the silt-find sand during the inter-glacier periods.
The underground water level was found around from about GL-5m in dry season to the ground surface level during rainy season.

3-5 Hydro-Geology of the Angkor Area

The Hydro geological map of Lower Mekong Basin compiled by A.Charuratna and T. Hong Phu (Mekong Committee, 1992) is also shown in Fig.3-7.
The surface geology of the Angkor area is quaternary sediments. These sediments are denoted as q_h(Quaternary; Holocene) and q_{pt}(Quaternary; Pleistocene to Tertiary) classified into a two groups by the age of sediments.

As noted in the preceding section, the most part of the Angkor area is covered by the Older Alluvium formation of q_{pt}. The Angkor Wat area locates at the edge of the Older Alluvium formation.
The thickness of the alluvial sediments near Siem Reap based on boring data exceeds more than about 30 to 40 meters. At west side of Siem Reap points there are boring data of the thickness to the base rock as 20 meters. It is not known the thickness of alluvial formation at the Angkor area. It is necessary to drill a reference boring to the base rock at some point in the area.
These formations are listed in Table 3-2

Table 3-2 Geohydrological Unit in Angkor Area

Geological Age	Unit	Description
Recent to Holocene (present-20,000years) q_h	Younger Alluvium Aquifer Tonle-Sap Formation	Alluvium deposits as sand, gravel, silt, and clay forming alluvial plain including buried channels. Low sediment terrace less than about 5m.
Pleistocene to Tertiary (older than 20,000years) q_{pt}	Older Alluvium Aquifer Battambang formation	Unconsolidated or semi-consolidated sediments of gravel, pebble, sand, silt, clay forming high sediment terrace along edges or basins or relatively low flat terrace. High sediment terrace higher than 10m.

(Hydrological Map of Lower Mekong Basin(1992))

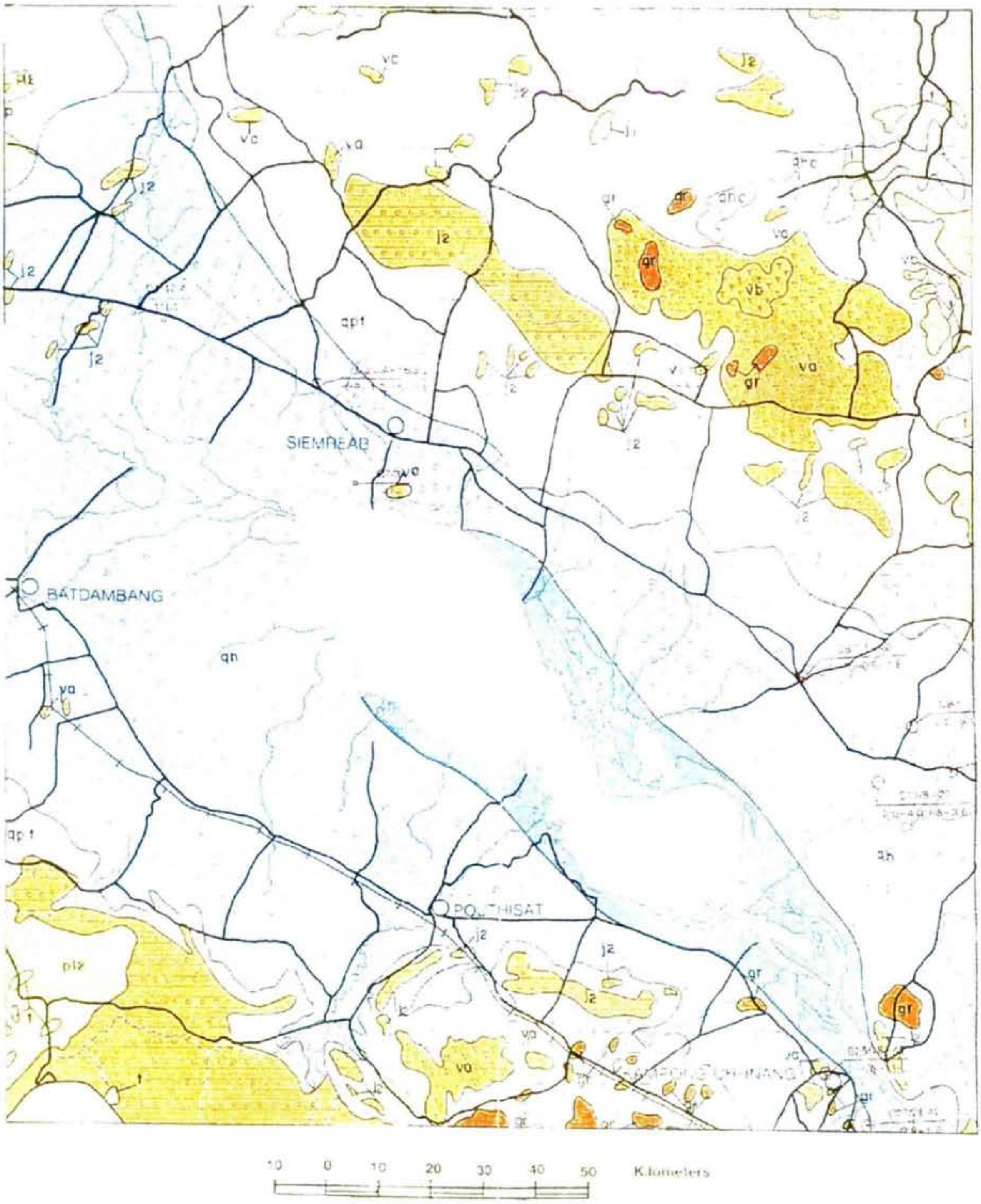

Fig.3-7 Hydrological Map of Angkor Region (Hydrological Map of Lower Mekong Basin (1992))

Fig.3-8 Legend of Hydrological Map of Angkor Region
(Hydrological Map of Lower Mekong Basin (1992))

Two well groups are shown in the Siem Reap area. The yielding capacity of the inland area is less than the coastal zone and classified as less than 5m^3/hour.

q_h formation(Coastal area):
Extensively well sorted sand and gravel are good aquifer. Average depth is 30-50meters. Water quality is commonly fresh. The yielding capacity of this formation is classified 5-30m^3/hour.

q_{pt} formation(Inland area):
Locally well sorted sand and gravel are good aquifer but mostly rather inferior due to poor sorted with clay matrix. Average depth is 30-50meters and good in water quality but locally high iron contents.

It is expected to keep constant water levels in ponds and moats to avoid settlements that have been found around the foundation of the surrounding structures nearby water lines.
It is important to study hydrological conditions in the area to consider the use of the water resources for watering the moats.
There are two resources of water. One is surface water of the Siem Reap River and another is underground water.
According to the geo-hydrological map of Fig.3-7, the Siem Reap area is covered by q_h and q_{pt} formations. The coastal area is q_h and inland area is q_{pt} formation. As noted earlier, the Angkor Wat and Angkor Thom locate about the boundary of these two formations.

3.6 Characteristics of Pumping Wells and Water in Siem Reap

The following is the summary based upon the collected information by Mr.Tomi Measu, on wells in the western region of Siem Reap city from 1994 to 1995then the member of JSA. The total numbers of wells surveyed is more than 1,000.

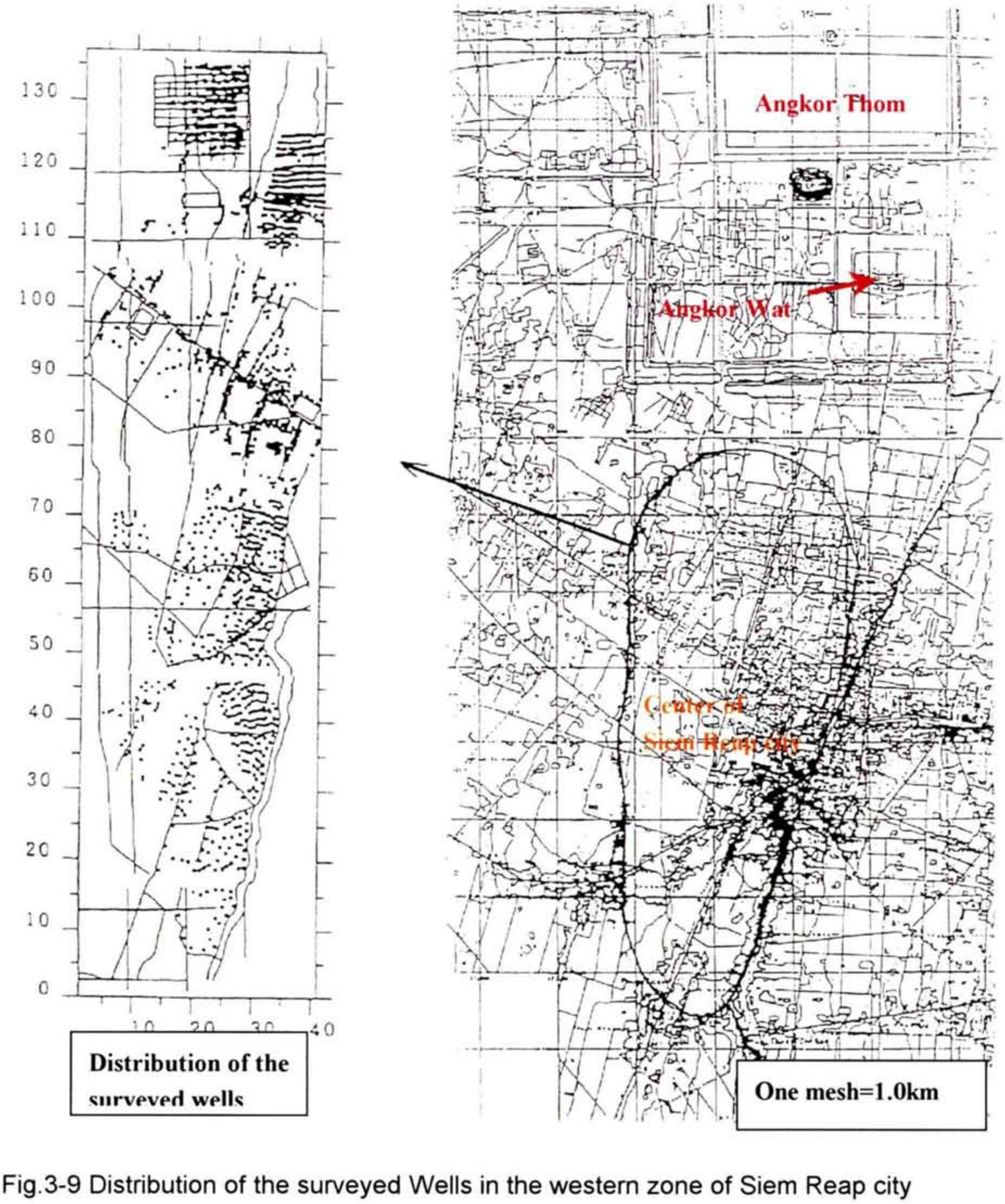

Fig.3-9 Distribution of the surveyed Wells in the western zone of Siem Reap city

The recent trend of concentration of people in Siem Reap city and the drilling well for domestic use of water every house have resulted in the increase of well to a large number compared in the past.

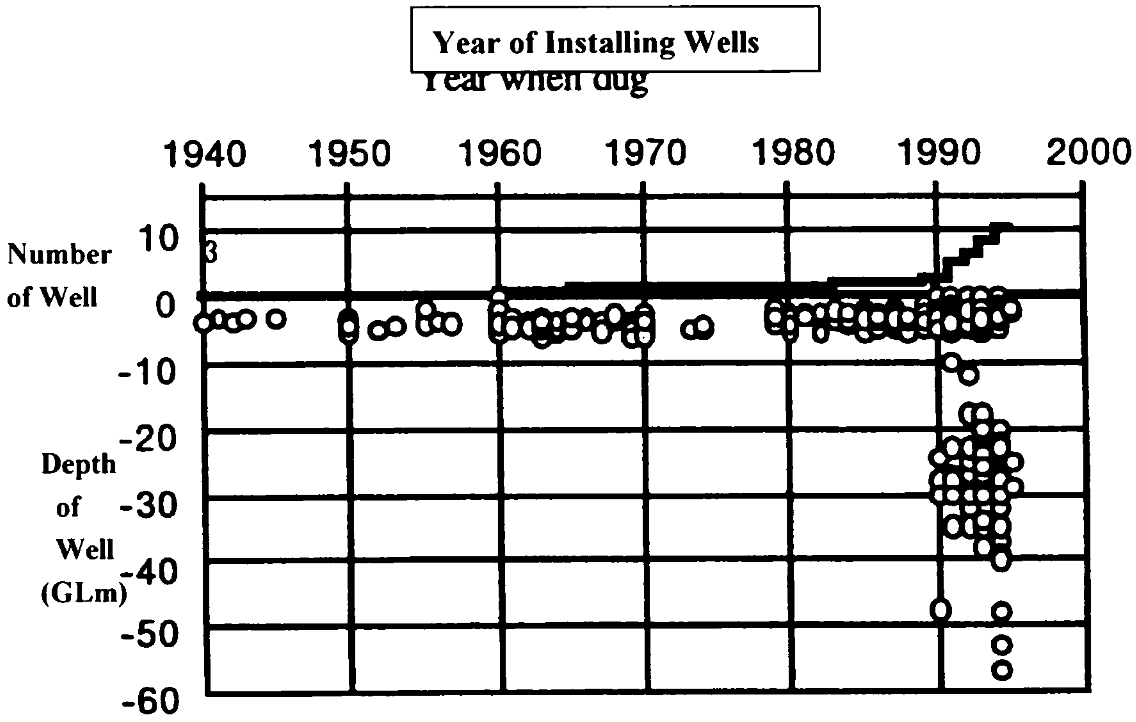

Fig.3-10 Increase of Number of Wells with Time and depth of Wells

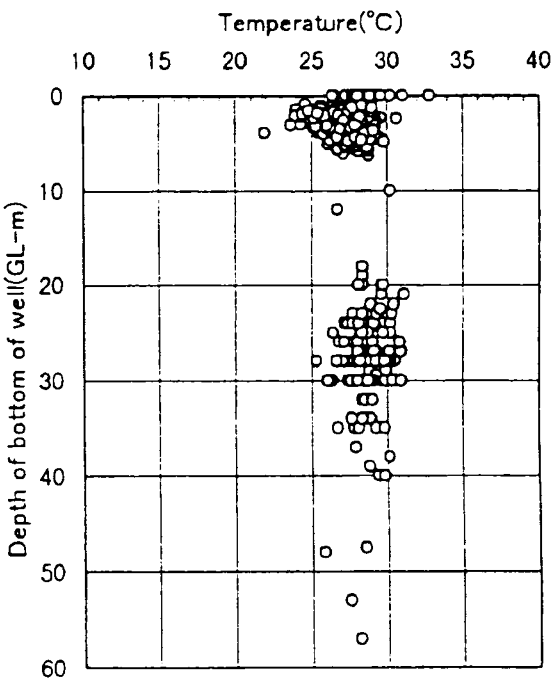

Fig.3-11 Temperature of Water sampled and Well Depth

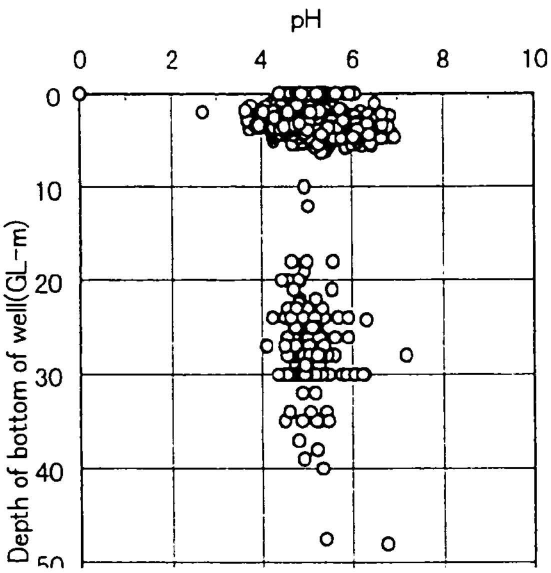

Fig.3-12 pH of Water sampled from Well

Fig.3-10 shows recent trends of increase of number of wells as well as the depth. Before 1970 when Lon Nol declared the Republic of Cambodia, the total number of wells was less than 200 and the well depth was shallower than 10m. These trends were seen until 1990.
After the International Conference resulted in peace treaty, people became to return to their home villages and the number of the wells became rapidly increased. The depth became increased from less than GL-10m to more than GL-20m to -60m.
Figs.3-11 and 3-12 show temperature and pH measured for sampled water from the well and the depth of the wells.
The temperatures of sampled water are found very much scattered within a range from 24 to 32°C. However, a gentle trend of increasing temperature with depth is found, which is consistent with an increase of 3 °C per 100m in general thermal characteristics of the earth.

The pH measured shows much wider range than these results obtained from the surface water shown in Fig.4-9. This acidic nature of the underground water is due to lateritic soils in the region. It should be noted that the shallower depth is quite different characteristics from the deeper one. The pH distributes from pH=3.5 to 7 for sampled water from the shallow well. The pH for the deep wells the distribution becomes less wider range of pH=4 to 6. The wider range of the shallower water may be from two reasons. One is high rate of bacterial decomposition of the vegetations and organic material in the shallow depth promotes acidification of the water. This yields very low pH. On the other hand, rainwater directly infiltrated with little contact with acid materials, the pH is kept around pH=6-7, which forms another high extreme group. The pH of the deeper well shows more stable distribution. The sudden decrease of the pH range from the shallow to deep well suggests the discontinuity between two underground water systems. The blank of the depth of the wells between 10 to 20m and 40 to 50m also indicates two independent impermeable layers in the Siem Reap region.

3.7 Conclusion

In this chapter, general characteristics of topology, geology, and geohydrology were discussed based upon not only with the past study but also with new borings and measured water quality. The first deep borings were performed in 1994 to study surface geology and base rock in Angkor area. The surface geology is lateritic soils with about 40m in thickness and SPT values of N=20 in average with increasing number with depth. The basic rock was found around 80m from the ground surface. Five borings to cover the area showed rather the same characteristics of geological formations.

Special attention was paid to the present states of underground water. The underground water that flows in the upper sandy silt layer is expected major resource of water supply in the area. The pumping wells in Siem Reap city were studied by a survey of more than 1000 wells for domestic use. The survey includes the depth of wells, pH values, and water temperatures. It was found that the depth of the wells has a definite trend of deepening with time from GL-5m in 1980' to more deeper than GL-30m in 1990'. The recent trend of deepening underground level in the Siem Reap city may be a warming of the shortage of water supply in the near future.

The lowering underground water may cause the settlement of the ground, which results in differential settlement of the stone monuments. The water supply problem is another big problem related with not only social development but also safeguarding monuments in Angkor.

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4 Metrological and Water Environmental Condition in Angkor Area

Among various information on the natural environmental condition in the Angkor area, rainfall and temperature are very basic fundamental subjects. We made efforts to find records of metrological observations in the area. Mr. Chim KDEP director of the Irrigation Office at Siem Reap, was very kind and provided us some of the records in the past several years.

Water environmental condition is one of the important subjects in the area and we have measured water quality at several sites in the Angkor area as well as a few points along Siem Reap river to the Tonle Sap Lake.

4.1 Metrological Records at Irrigation Office at Siem Reap

4.1.1 Rainfall

The precipitation record at the Siem Reap Irrigation Office can be trace back to the data in 1979. Monthly rainfall data of 15 years from 1979 to 1993 are plotted in Fig.4-1. The averaged monthly rainfall with standard deviations is shown in Fig.4-2. It is clear that the area belongs to a unique zone where the rainy and dry seasons come alternatively in a year. Rainy season starts in May and ends in October. Dry season starts in November and ends in April. The rainfall in the rainy season is recorded about 200 mm per month and less than 50 mm per month in dry season.

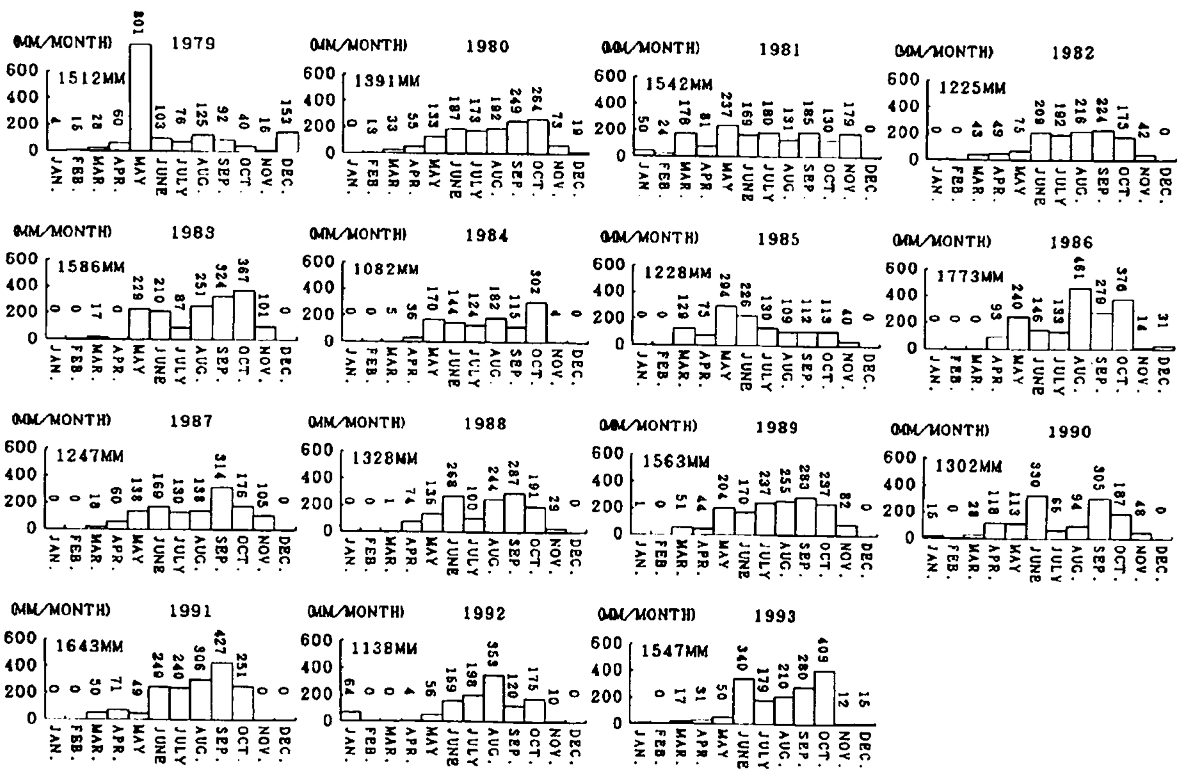

Fig.4-1 Monthly Rainfall from 1979 to 1993(data from Siem Reap Irrigation Office)

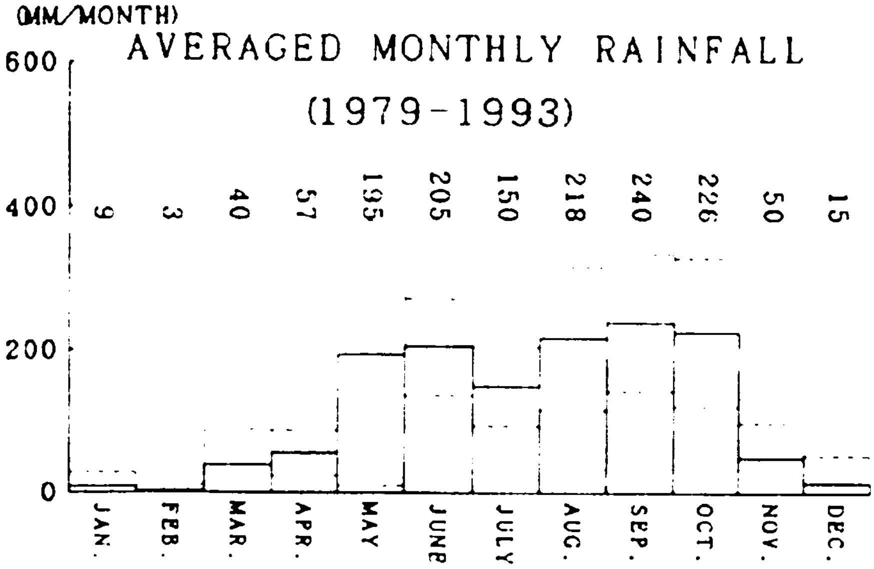

Fig.4-2 Averaged monthly rainfall (data from Siem Reap Irrigation Office)

The end of the very dry season of April, it becomes the hottest time in the area and the glasses and trees dries to their death of lives.

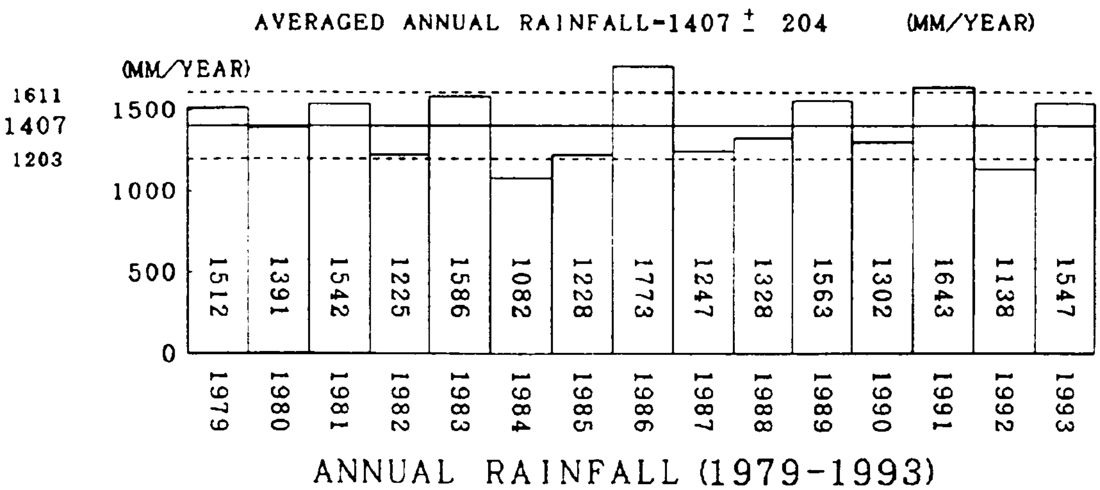

Fig.4-3 Annual rainfall from 1979 to 1993 (data from Siem Reap Irrigation Office)

Fig.4-3 shows the annual change of rainfall from 1979 to 1993. The average is 1407mm, which is the same level as in Bangkok (1492mm) or in Tokyo (1405) and 2.5times larger than in Almaty (640mm).

4.1.2 Wind

Wind data consists of the averaged month velocity, extreme maximum wind velocity in a month, as well as wind directions of the extreme maximum velocities. Recorded data was provided for five years from 1989 to 1994. The averaged monthly velocity and the extreme maximum wind velocities are shown in Fig.4-4. The monthly distribution of the wind directions of the extreme wind velocity is also shown in Fig.4-5.

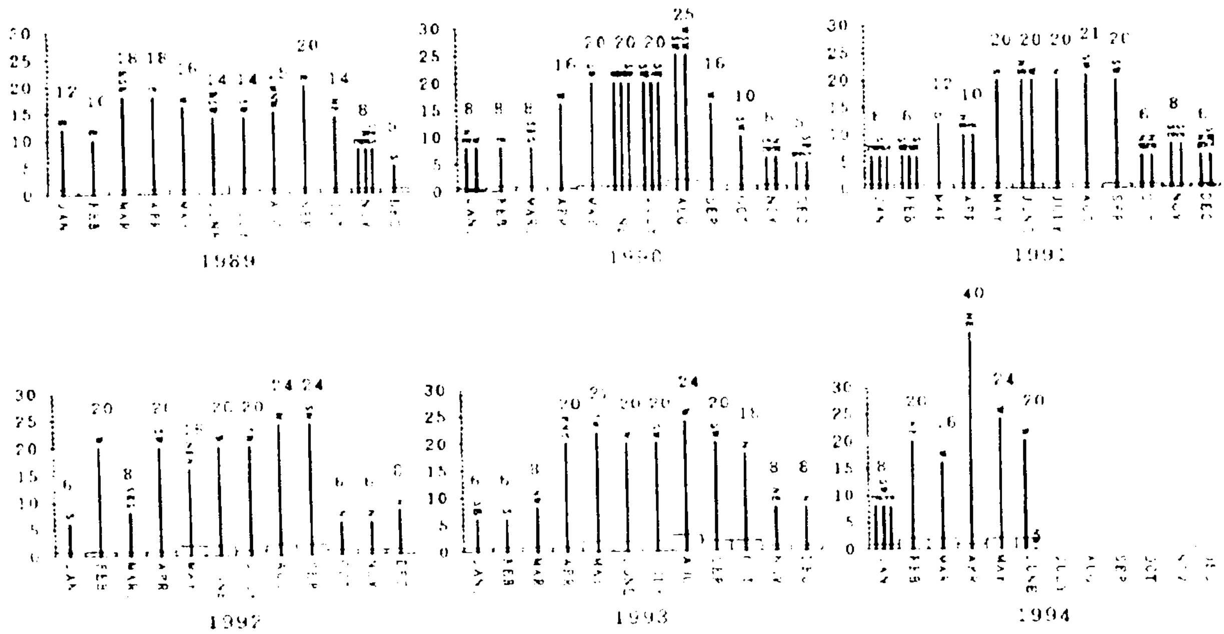

Fig.4-4 Averaged monthly wind velocity and the extreme maximum wind velocity (m/sec) (data from Siem Reap Irrigation Office)

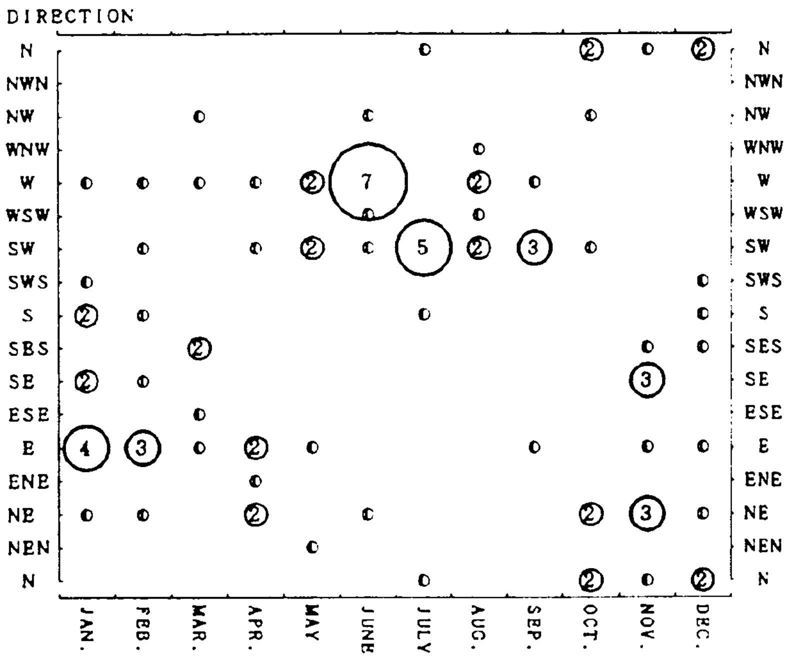

Fig.4-5 Averaged monthly wind direction of the extreme maximum wind velocity. (data from Siem Reap Irrigation Office)

Even though the averaged monthly wind velocity is only less than a few meter per second, the extreme wind velocities have been recorded about 20 m/sec. and even reaches to 40 m/sec. It is seen that the stronger wind blows in rainy season than dry season.

The distribution of the wind directions of the extreme wind velocities is also of great interest. As shown in Fig.4-5, the predominant wind direction is west in the rainy season and is east in the dry season. This is one of the characters of the monsoon climate in the area.

4.1.3 Temperature

Temperature records are available from 1979 to 1984 to show the monthly change of the maximum and minimum temperature in a month as plotted in Fig.4.6.

The averaged monthly change is also shown in Fig.4-7, the averaged maximum temperature is within 38.8 in April to 32.0 degrees in Centigrade in October. The minimum temperature is from 16.0 in December to 23.6 in May. Generally the temperature in the area shows rather constant and varies within 16-37degrees in Centigrade.

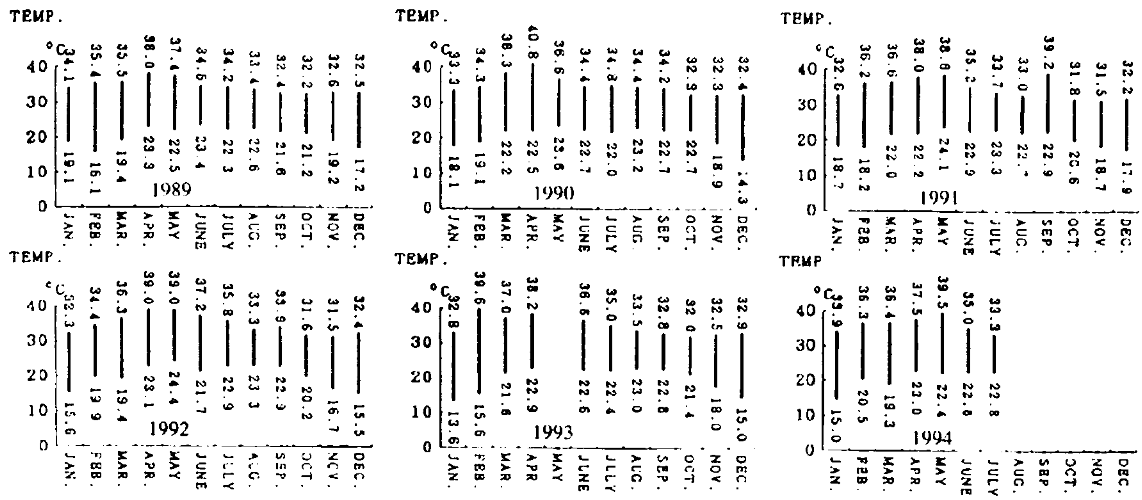

Fig.4-6 Monthly temperature change from 1989 to 1994. (data from Siem Reap Irrigation Office)

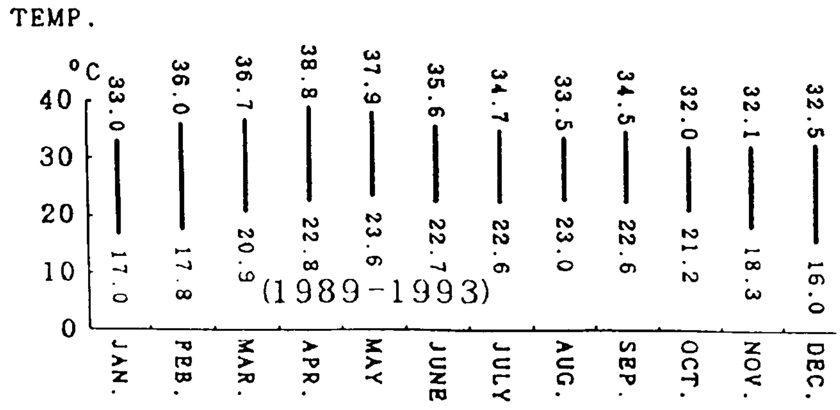

Fig.4-7 Averaged monthly temperature change. (data from Siem Reap Irrigation Office)

4.2 Water Environment at Angkor and along Siem Reap River

To study water environmental conditions in the Angkor area, we sampled water along Siem Reap River at several sites as well as wells around the Monuments. The quality of water gives strong effects on the stone monuments.

We used a compact hand carry type equipment to test the water quality for general characteristics of water.

The sampled sites are listed in Table4-1 and shown in Fig.4-8.

The test items were pH, Electric Conductivity, Dissolved Oxygen, and Temperature.

Table-4-1 Water Sampled Site for Its Quality Tests

Site	Sample Condition	Sampled Site	Date
1	natural rain	at Diamond Hotel, Siem Reap city	Aug.5, 1994
2	pond water	north pond, Prasat Sour Prat	Aug.3, 1994
3	surface water	near sample point A-No.1	Aug.3, 1994
4	under ground water	borehole A-No.1(WL=GL-0.59m)	Aug.3, 1994
5	under ground water	borehole A-No.3(WL=GL-0.59m)	Aug.3, 1994
6	deep open well(-30m)	deep well in Bayon temple	Aug.1, 1994
7	shallow well	south of Bayon temple	Aug.1, 1994
8	deep well	south of Bayon temple	Aug.1, 1994
9	deep well	Angkor Wat within outer wall	Aug.2, 1994
10	river water	Siem Reap River at Diamond Hotel	Aug.3, 1994
11	river water	South of Siem Reap city	Aug.3, 1994
12	Lake water	Tonle Sap Lake	Aug.3, 1994
13	ground surface water	Quarry of Phnon Krom Mountain.	Aug.1, 1994

4.2.1 pH;

pH is designated as the negative reciprocal of the logarithm of hydrogen-ion concentration. The pH of the surface water shows 6.0-8.0 in general. The acidic nature of the humus, which is resulting from the partial decomposition of plants and animals, gives a tendency of lower pH values in the under ground water. The recent acidic rain also plays an important role to control the pH of the natural rain. Since the deviation from the neutral pH value (pH=7.0), the acidic or alkaline water causes undesirable chemical reactions to water supplying pipes, the pH value is recommended within a certain range. The range depends on the organizations.

Table-4-2 Recommended Range of pH

WHO	pH;	7.0-8.5
Japan	pH;	6.5-8.5

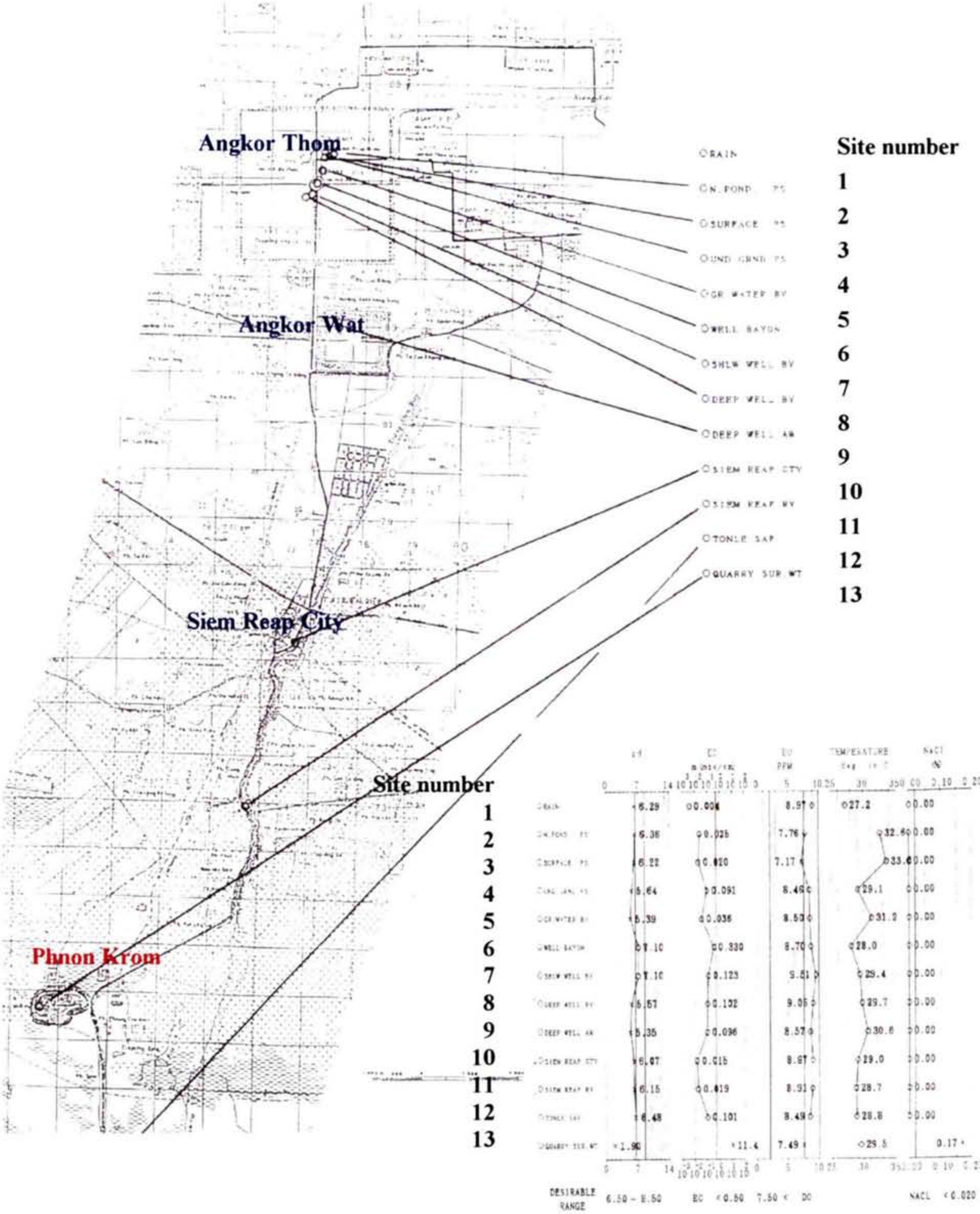

Fig.4-8 Sampled site along Siem Reap River Fig.4-9 Results of Water Test

The pH values of rain usually show pH=5.6 of weak acid nature in Japan, where the rain contains fully dissolved CO_2.

$CO_2 + H_2O > H_2CO_3 > H^+ + HCO_3^-$

However, the small particle that becomes core of rain consists of much of the sea salt. The component of the rain core acts as to increase the pH of the rainwater.

If the pH of the rain is less than this value, it is called as acid rain. The pH values of recent rain in Japan ranges from about 4 to 7, the average value is pH=4.5-4.7 and considered as effected by the acid rain.

The rainwater shows pH=6.29, higher than the averaged value in Japan. This is due to the high temperature of rain which results in decrease of full dissolved CO2 in the rain. The most sampled water were pH<6.5, which does not satisfy the environmental standard.

There is a special point of No.13, where the surface water trapped in a small hollow place. The water was colored in brown. The pH measured was pH=1.90 of strong acid.

4.2.2 Ec; Electric Conductivity (mho/cm)

The electric conductivity is defined as a reciprocal number of the resistance of the liquid with $1cm^2$ in section area and 1cm in length under 25°C. The conductivity depends the concentration of dissolved ions, especially the concentration of salt in water. Recent study on various stone weathering, salt concentration of underground water have been found one of the important reason to accelerate chemical weathering process. The high electric conductivity may also give negative effect on plant growth. The desirable range is less than about 0.001 mho/cm for plantation and 0.0005 mho/cm(=0.5m mho/cm) for fish growing in fresh water.
Except at No.13, where the sample showed very large conductivity of 11.4.

4.2.3 DO; Dissolved Oxygen

The maximum amount of the oxygen that is dissolved in water depends upon pressure and temperature. If the oxygen dissolved in the water is less than the maximum value, some organic matters might have contaminated the water. The DO is an index to show the degree of the organic contamination. The maximum dissolved oxygen under 30°C and one atm (atmospheric) air pressure condition is 7.63ppm.

The DO value for water and lake in Japan is recommended as more than 7.5ppm for natural environment condition and more than 5ppm for agricultural use. The No.13 point shows small value of 7.49.

4.2.4 Temperature

Temperature of water in Angkor is relatively high throughout year. The temperature of rainwater shows 27.2°C. The ground surface water is warmed by ground temperature and shows 32-33°C. However, the water temperature becomes lower and stable around 28-29 °C as the Siem Reap River reaches to Tonle Sap Lake.

4.2.5 NaCl

The coastal area near sea, the salt contamination into fresh water is one of the environmental problems. The high concentrated water is not good for drinking and it causes damages to not only stone monuments but also to plantation.

The threshold value of concentration of salt is 0.02% for drinking water and 0.03-0.07% for agricultural use by Japanese standard.

4.3 Conclusions

Meteorological data supplied by Siem Reap irrigation Office shows basic nature of the natural environments under tropical and monsoon climate. The recorded data shows the area is in the Asian monsoon zone, where distinct two seasons of rain and dry exist. Rainy season starts in May and ends in October, when averaged rainfall is 200mm/month. Dry season is from November to April, when the averaged rainfall is 50mm/month. The high temperature with rain in the area resulted in producing laterite soils and in easy decay of laterite blocks.

It is noted that little rain was recorded in the mid dry season from December to February. Temperature in April reaches almost 40°C. When April comes, the Siem Reap River sometimes dries up with little stream.

At the time measured, quality of water showed rather within safe range. The constant monitoring is necessary to assess the water-environmental situations in the Angkor region.

Angkor in the old days was a city of water with many canals, on which boats were used as basic traffic measures.

The Siem Reap River that flows along the various monuments in Angkor is the symbol of the aqua-city and should be kept clean especially dry season.

4.4 Reference

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5 Geotechnical Characteristics of Angkor Region

We performed field surveys to study geotechnical characteristics of the ground in addition to the borings. They are dynamic cone penetration test and soil augur sampling.

The dynamic cone penetration test at nine sites was conducted to see the strength characteristics of the upper surface geo-material. We also obtained soil samples by hand augur sampler at the same sites at the dynamic cone penetration test. The sampled soils were further tested to obtain various physical properties of soils.

Fig.5-1 shows the points where the field tests were conducted.

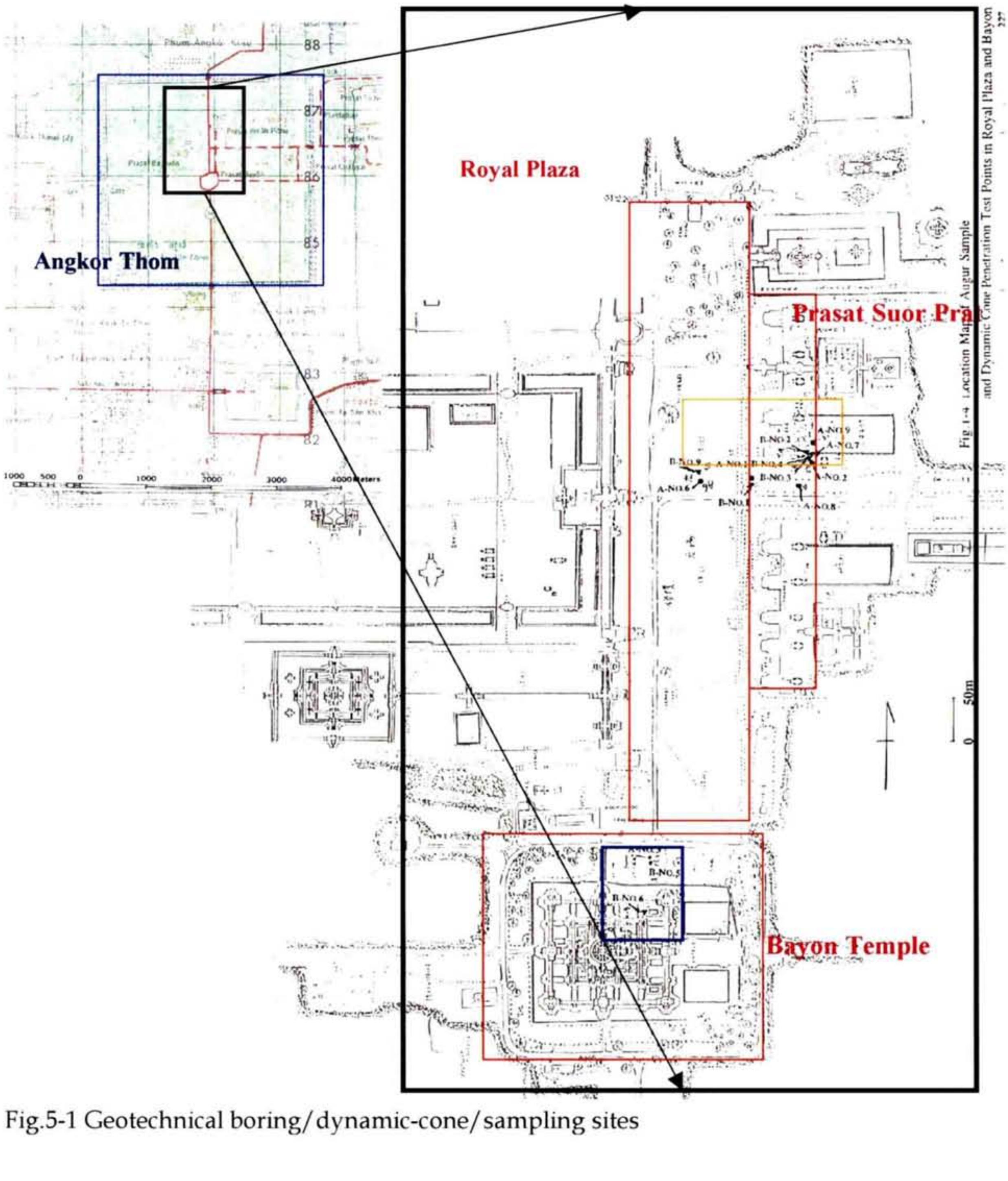
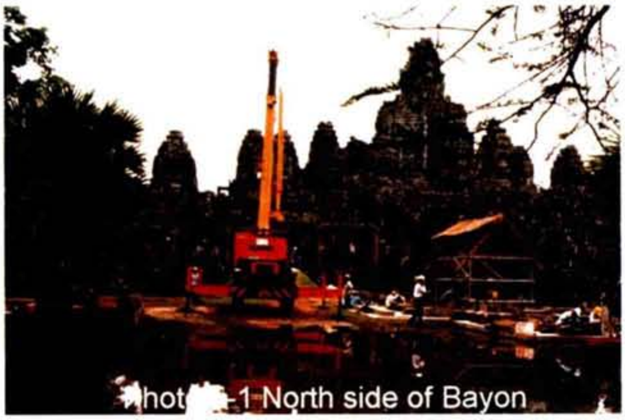
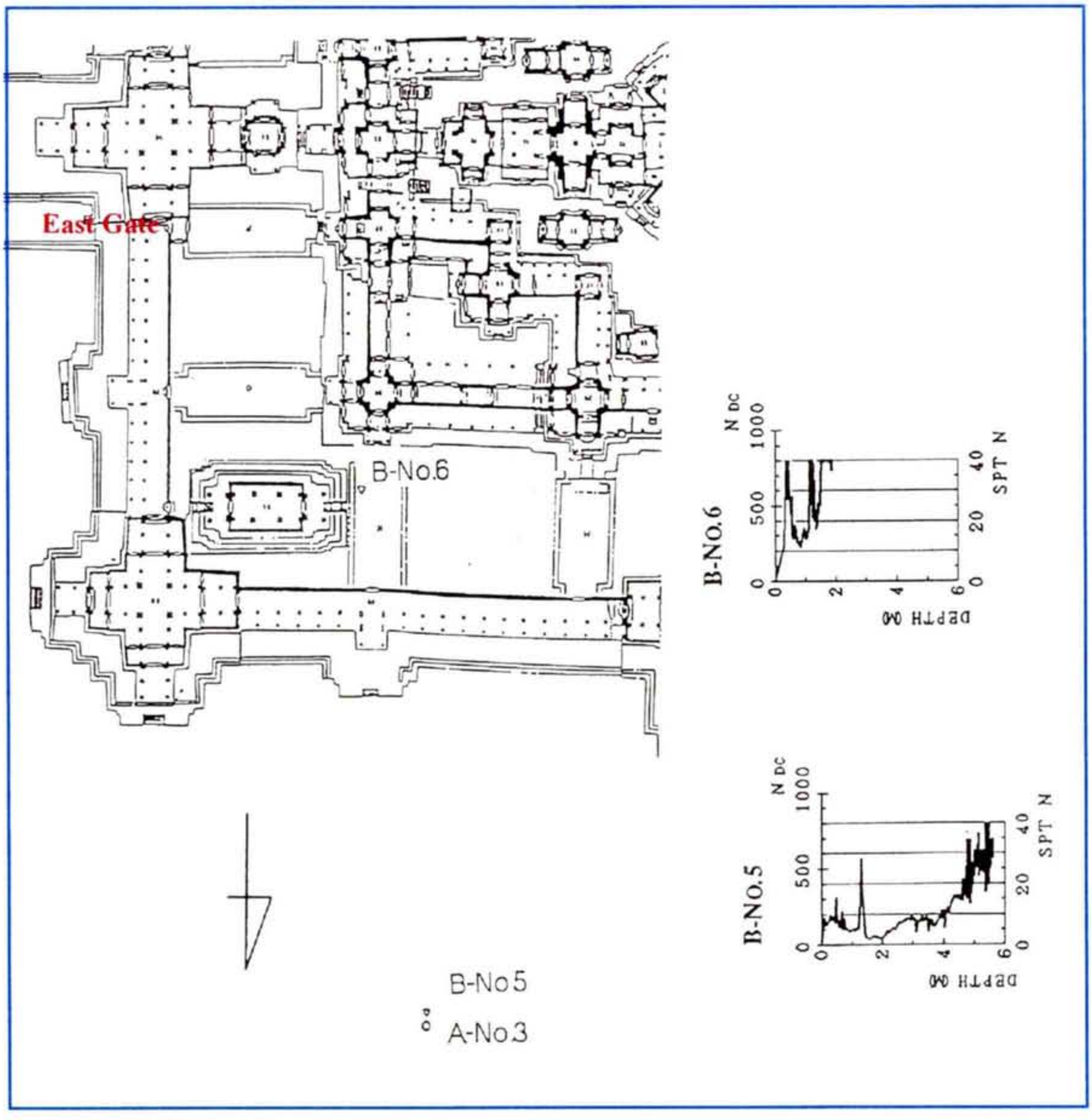


Fig.5-1 Geotechnical boring/dynamic-cone/sampling sites

5.1 Dynamic Cone Penetration Field Test

To obtain strength characteristics of the surface ground, dynamic cone penetration test was conducted in several points. Dynamic cone penetration test is to study ground resistance by counting number of blows by falling weight (mass: 6.5kgw) from 50cm height to the rod with head cone (diameter: 30mm, conical angle, 60degrees).





. Fig.5-2 Dynamic Cone Test in Bayon Temple (see the zone in blue line in Fig.5-1 corresponds with Fig.5-2 except the opposite in north-south direction.)

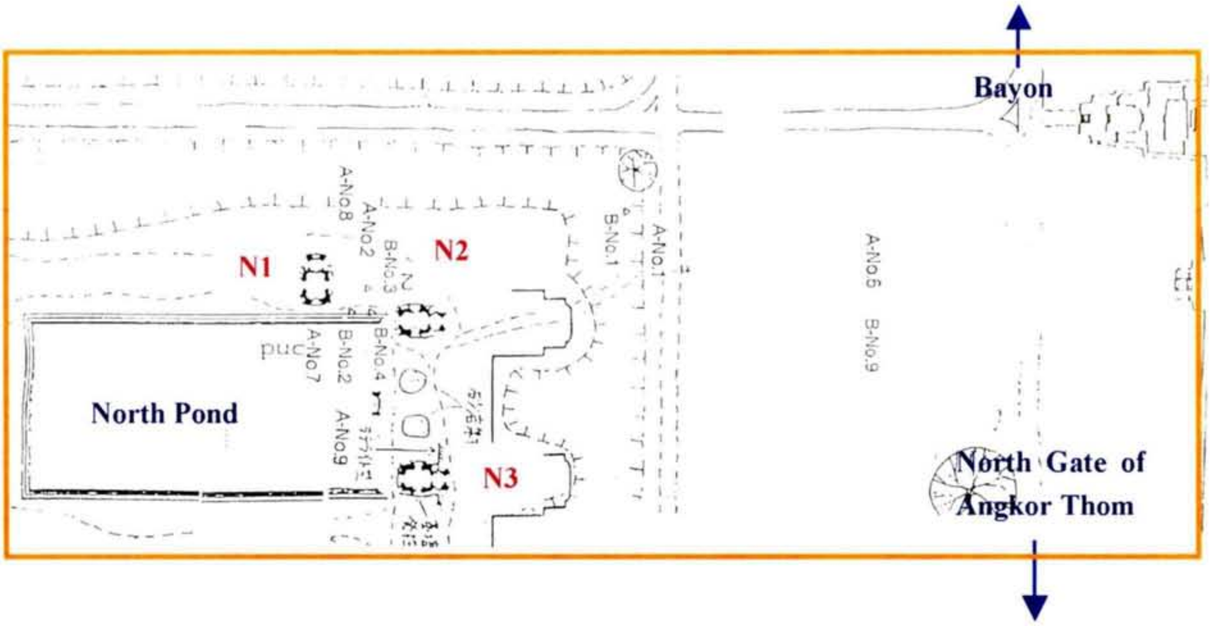


Fig.5-3 Geotechnical survey around Prasat Suor Prat Tower N1, N2, and N3

Photo 5-2 Royal Plaza and Prasat Suor Prat from North

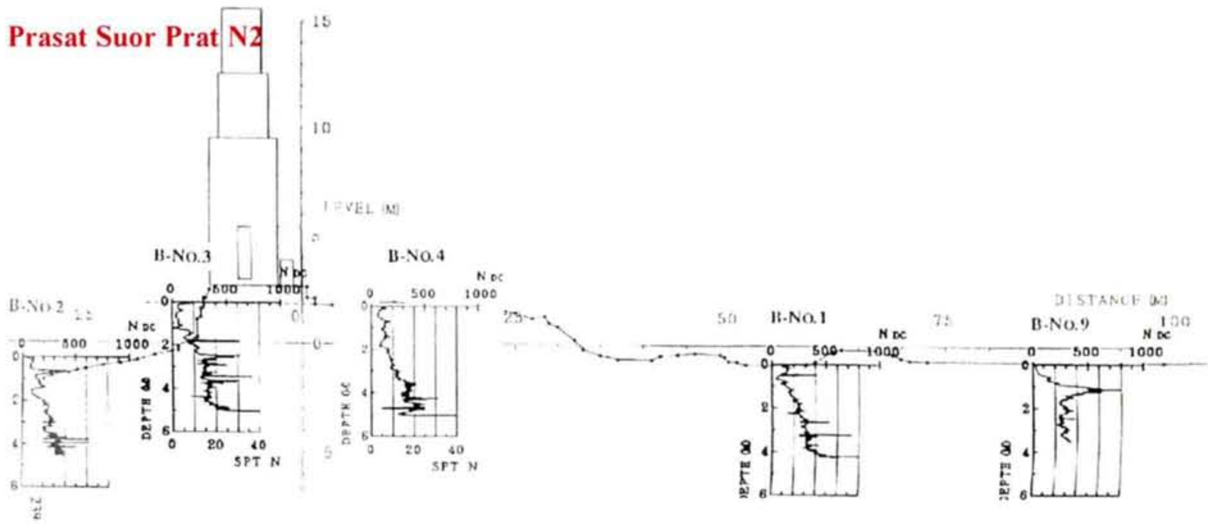


Fig.5-4 Results of Dynamic cone resistance near Prasat Suor Prat N2 and Royal Plaza

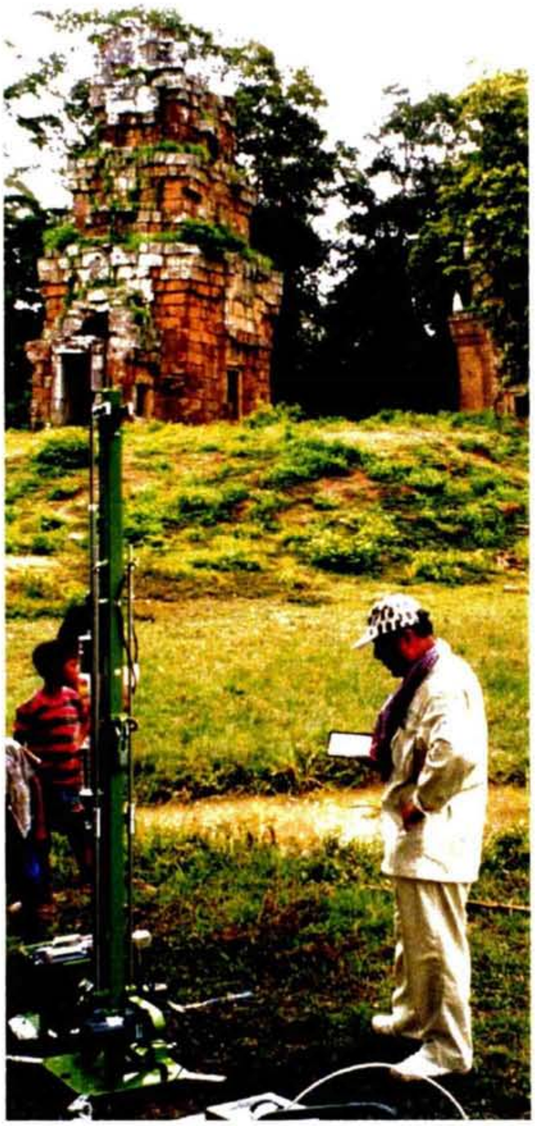


Photo5-3 Dynamic Cone Test in front of Prasat Suor Prat

The length of a rod is one meter and an extension rod is to be connected every one-meter depth if the sounding depth exceeds one meter. Results of dynamic cone penetration at north of Bayon temple B-No.5 and B-No.6 are shown in Fig.5-2.
The testing results are recorded in a chart, which runs with the rod movement with a tic symbol drawn on chart for every blow. The number of blows required per unit penetration is read and the number is converted to blows per one meter, N_{DC} (blows/m). The relationship between this dynamic cone test result and the standard penetration test is not yet established yet, N_{DC} is tentatively correlated with the N(blows/0.3m)=N_{SPT} value by standard penetration test as follows,

$$N_{DC}(\text{blows/m})=20\ N_{SPT}(\text{blows/0.3m})$$

The testing results are recorded in a chart, which runs with the rod movement with a tic symbol drawn on chart for every blow. The number of blows required per unit penetration is read and the number is converted to blows per one meter, N_{DC} (blows/m).

The following table gives relation of consistency of clayey soils and N-values.

Table 5-1 Tentative Relation of $N_{,STP}$ vs. N_{DC}

Consistency	values(N_{SPT})	Ndc
Very Soft	N<2	<40
Soft	2<N<4	40<Ndc<80
Medium	4<N<8	80<Ndc<160
Stiff	8<N<15	160<Ndc<300
Very Stiff	15<N<30	300<Ndc<600
Hard	30<N	600<Ndc

. A soil sampling was performed at very near point (A.No.3) to the dynamic cone test. The soil test results of sampled data are also shown in Figs.5-7 and 5-8.

The Ndc is plotted with depth in Figs.5-7and 5-9. Generally Ndc increases with depth and Ndc exceeds 200 at the depth larger than a few meters and the ground is considered as stiff clayey ground.
Top subsurface of 2 to 3 m is soft to medium clay. At the point (B.No.6) west of north library at Bayon, the penetration was rejected by laterite block, which may be a part of foundation system of the library. Some places (B.No.5 at Bayon and A.No.8 at North Library inside of the outer wall, Angkor Wat) showed softer characteristics than the average tendency. At Prasat Sour Prat, Towers are built upon filled material. The thickness of the fill is about two meters and is found soft (Ndc<50) in the layer less than 1.5m from the surface.
Samples were taken at seven sites near to the dynamic cone tests (four for Prasat Sour Prat, one for Bayon, two for Angkor Wat). Other two points were added to see the soil profiles at Prasat Sour Prat.
The maximum depth of the sampling is a matter of how much time we can spend at one site. The upper portion of the soil contains plant roots. Sometimes, earthen-wares were found in the surface layer, which implies that these layer are artificial fill or the surface layer sediments after the human activities in archeological period.
At the boring site of A-No.9 in the north pond at Prasat Sour Prat, the earthen-wares were found throughout the sampled soil down to the bottom of the 2.0m. There is still a possibility of the existence of earthen-wares below 2.0m in depth from the surface. At the depth of 1.2m from the surface, there is a peaty layer which implies that the time might exist when the sedimentation stopped and the surface of the ground had been kept some time to allow the peat had grown.

5.2 Physical Characteristics

Laboratory tests for sampled soils are as follows,

1. grain size distribution
2. specific density
3. natural water contents
4. pH test
5. mineral analysis
6. liquid limit and plastic limit for clayey soils

Photo 5-4 Lateritic soil

The surface soils are brown sand to silty or clayey sand. Generally, the color of the brown to reddish brown comes from ion oxides as shown in Photo 5-4.

5.2.1 Grain size distribution

The grain distributions of sampled specimen for three sites of Bayon, Prasat Suor Prat, and Angkor Wat are shown in Fig.5-5.

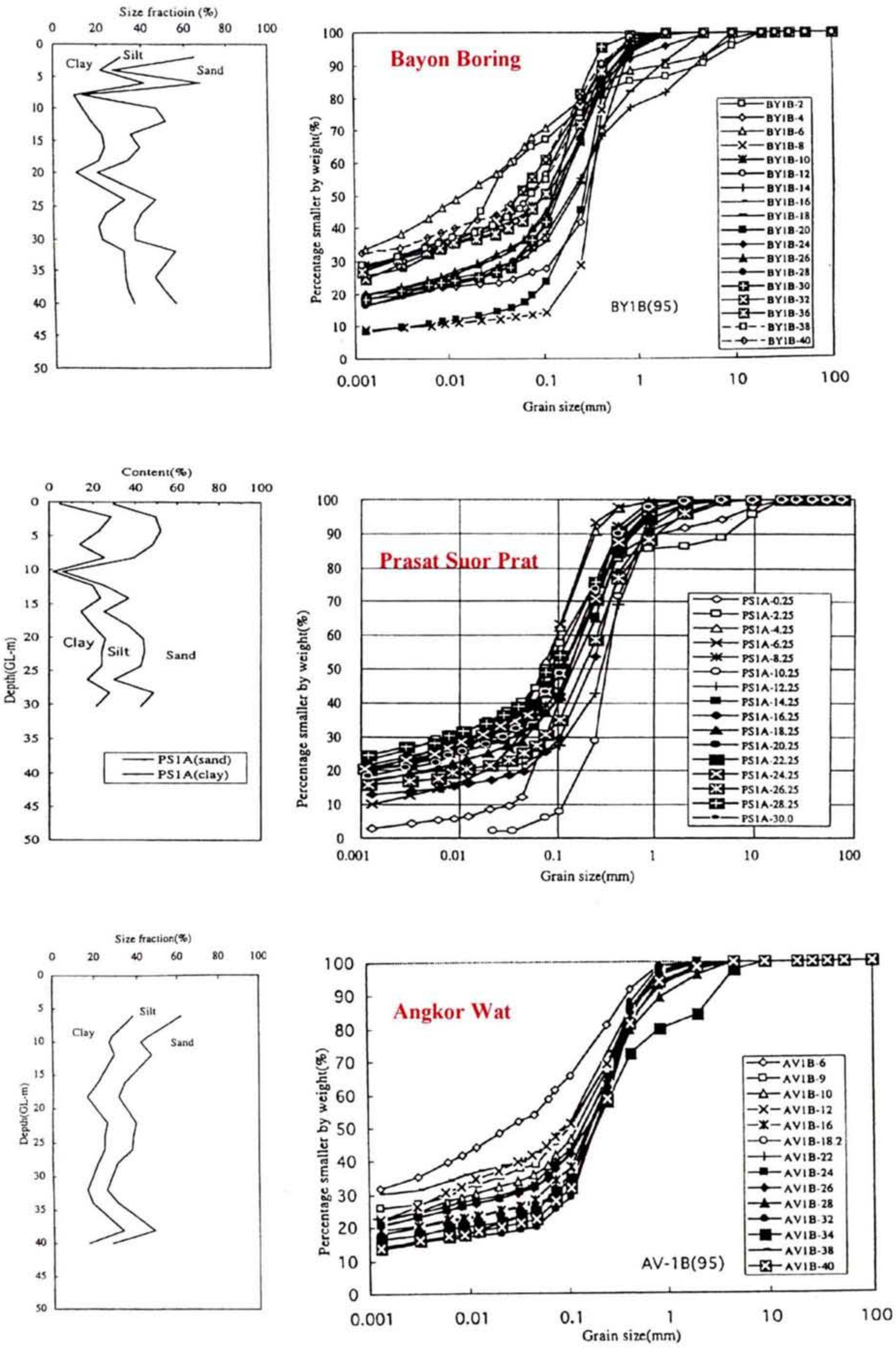


Fig.5-5 Grain-Size Distribution of Bayon, Prasat Suor Prat, and Angkor Wat

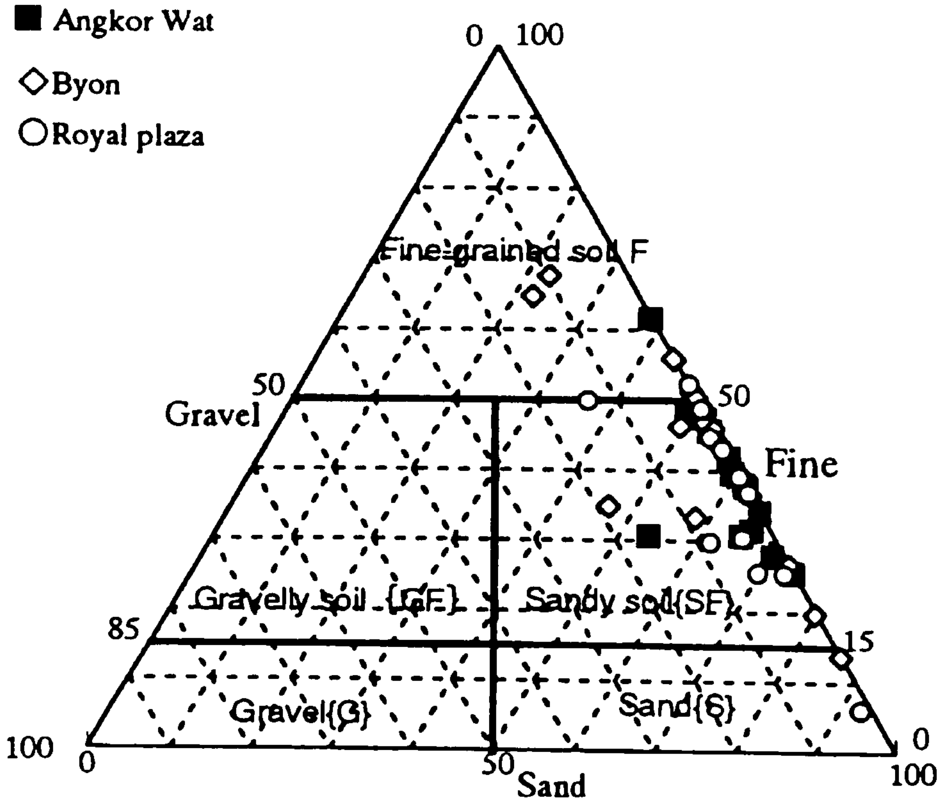


Fig.5-6 Soil Classification Chart Triangle Coordinate

Vertical variations of soil strata are found in every sites. however. the upper 40m grounds are found to consist of well graded sandy soils with silt fraction.
Based upon these grain size distributions. grain size characteristics were simplified into three components of sand (2.00mm>d>0.075mm). silt(0.075>d>0.002). and clay(0.002>d). Fig.5-10 shows the distribution of these three components of the soils in the tested results. It is found that the most soils are classified into sandy soil with fine material (SF).

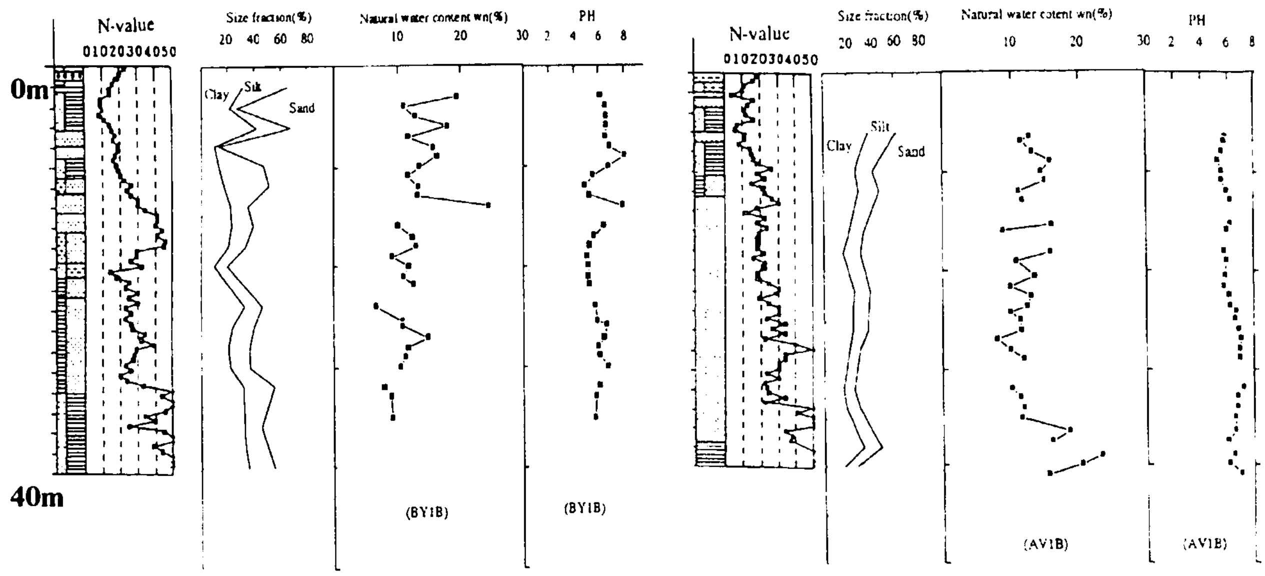


Fig.5-7 Change of water contents and pH with depth at Bayon and Angkor Wat.

Table 5-2 summarizes grain size distribution.

Table 5-2 Grain size distribution of soils top surface (shallow than 40m)

Soil type	Clay	Silt	Sand	Specific Weight of grain
Grain size range	<0.005mm	0.005<<0.075mm	0.075mm<	
Weight percents	25±9%	18±9%	57±14%	2.614±0.023

5.2.2 Natural water contents and pH test

The depth change of water contents of soils sampled at Bayon and Angkor Wat sandy are shown in Fig.5-7 with pH values. Water contents decreases with depth for both sites with some fluctuations due to some variations. This trend corresponds to the increase of SPT N values with depth. The trend of change of pH with depth at Bayon shows decrease of pH in the lower layer which is the same trend of those for water from wells in Siem Reap city. The pH values at Angkor Wat show rather opposite trend. These pH characteristics with depth may depend various factors of chemical components of soils but also flows of under ground water.

5.2.3 Specific Density

Specific density (Gs) distributions along depth are shown in Fig.5-8.

The averaged values for each site are

Bayon	2.614
Prasat Suor Prat	2.638
Angkor Wat	2.629

Specific density depends on the minerals that compose soils.

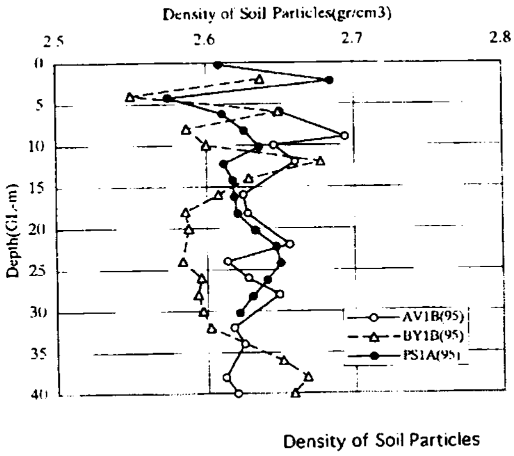


Fig.5-8 Depth change of density of soil particle

5.2.4 Mineral Analysis by X-ray diffraction

X-ray diffraction analysis on soil samples was performed by Prof. Uchida, Petrology Unit, JSA.
The predominant minerals in the upper 40m from the surface are quartz (wave length =3.34A) and kaolinite(wave length=3.32-3.22A). Specific gravity of quartz and kalolinite are shown in Table 5-3.

Table 5-3 Specific Gravity

Mineral	Specific gravity
Quartz	2.65-2.66
Kaolinite	2.60-2.63

These values are well coincide to the measured specific gravities of sampled soil shown in Fig.5-8.

5.2.5 Liquid limit and plastic limit

The liquid and plastic limits are obtained for fine contents of sampled soils. The averaged values are shown in Table 5-4.

Table5-4 Water content and the Atterberg limit

Natural *w c*	Liquid limit *Wl*	Plastic limit *wp*	Plasticity Index *Ip*
10-11%	37±11%	11±3%	27±10%

The liquid limit ranges in 30-40% and plastic limit in 9-14%. Since the average natural water content was 10-11%, which is the same value of the plastic limit. These low values of natural water contents as the same of plastic limit indicates the relatively stable states of the surface soil layers.
It may not be expected that large settlement like in Bangkok will take place due to consolidation of the surface layer.

5.3 Shallow surface ground

The deep borings were performed during March to May, dry season in the area. On the contrary, dynamic cone tests were carried in September to October of rainy season.

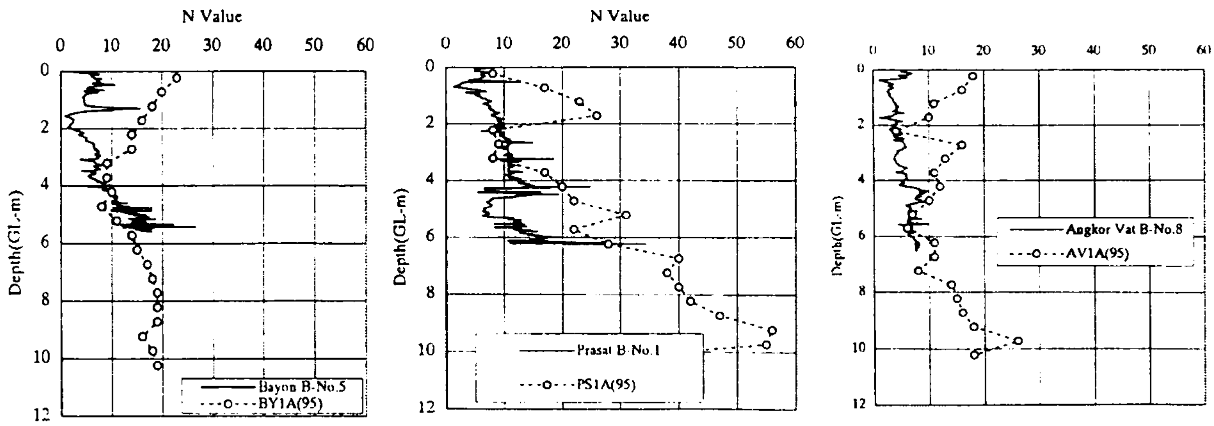


Fig.5-9 Comparison of SPT N-value (white circle/dry season) vs. Dynamic cone (solid line/rainy season)

The comparison between the SPT values against dynamic cone resistance number was shown in Fig.5-9. The dynamic cone resistances were converted $N_{SPT}=N_{DC}/20$. It may be concluded the surface will become hard due to desiccation of the surface during dry season. These effects are found down to 5-6m in the area.
The detailed soil formations based upon the augur sampling at Bayon is also shown in Fig.5-10. The sample was retracted down to about 3.5m from the surface.

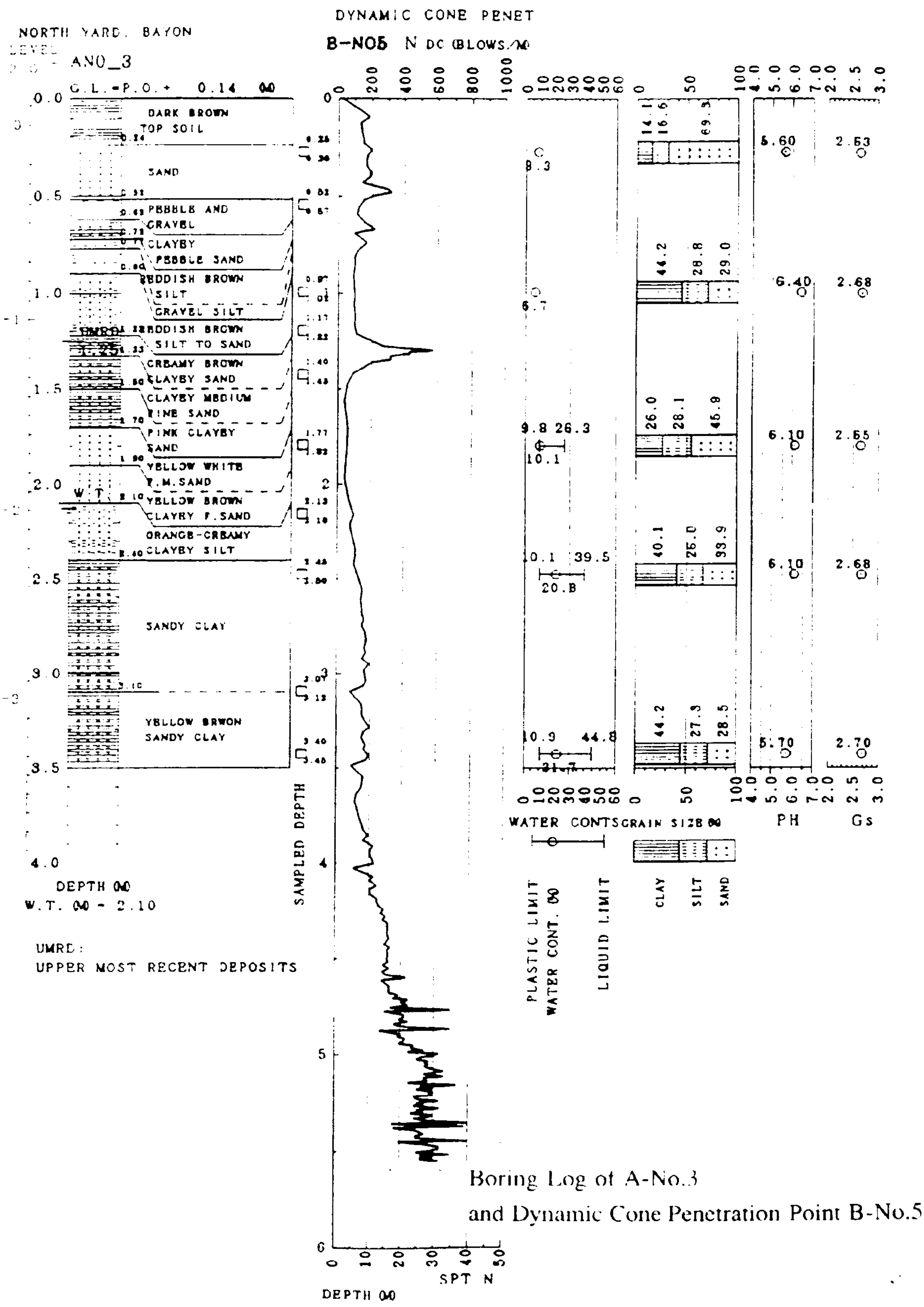


Fig.5-10 Results of Dynamic Cone Test (B.No-5) and Soil Characteristics for sampled at A.No-3

As shown in Fig.5-10, the upper surface soil is much more complicated than shown in the conventional drilling with SPT sampler. Alternations of sandy and clayey layers are predominant, which makes much easier horizontal flow of underground water. The rainwater infiltrates into ground may not only form vertical flow as well as horizontal one.

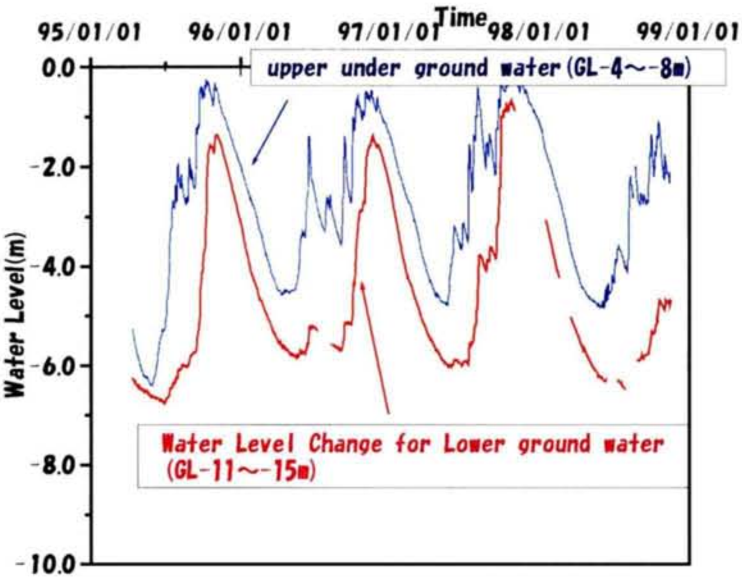


Fig.5-11 Seasonal change of level of underground water at Bayon site

As an example, the result at Bayon site is compared in the following discussion.
After drilling the deep boreholes, we have installed water pressure sensor to measure seasonal change of water level. In Bayon, a shallow depth from GL-4m to GL-8m and a deep depth from GL-11m to GL-15m were selected for measurement formations. As shown in Fig.5-11, two lines of under ground water level were shown. The blue thin line corresponds to the upper ground water and thick red one to the lower ground water.
The seasonal change of water level is seen as large as five to six meters, which may cause the drying and wetting of the top surface layer.
The N-value of the standard penetration by the boring is very large at the top surface and decreases with depth. On the other hand, the cone resistance, which is converted into equivalent N-value for comparison, shows the increase with depth. The different characteristics of this soil strength are considered as seasonal change of the ground.
The boring was carried out in dry season of February 1995. The cone penetration test was performed in rainy season of August 1994. The water level at the Bayon site is measured at two depths of shallow (from GL-4 to -8m) and deeper (deeper than GL-11m) sand layers. The seasonal change of these water levels is shown with daily rainfall in the later Section. The water level becomes highest at the end of rainy season of about 1-2m from the ground surface, which is 4-5m higher than that of the lowest level at the beginning of the rainy season.

The strong effects are wetting and drying of the top surface ground during these seasons. The soil becomes very stiff in dry season and shows very high strength. On the other hand the soil becomes soft in rainy season and shows rather weak in strength. The top 4-5m from the surface was found heavily affected by the seasonal effects.

The water level in the upper sand layer is one meter in dry and 2-3 meters in rainy season higher than that in the lower layer. The change of water level in the lower layer is very similar but delayed by one and half months than that in the upper layer. The water level reaches its maximum of GL-1m to -2m at the end of rainy season of October-November and its minimum of GL-4m to GL-7m at the end of the dry season of May-June.

The shallow ground of upper 5-6m may be unstable due to the seasonal changes of the water level.

5.4 Conclusions

Based upon dynamic cone penetration test and augur soil sampling, we obtained the geotechnical characteristics of the ground.

1. Top surface of about 40m in thickness is found lateritic soil as a common ground in the area based upon several geotechnical boring as described in the preceding chapter.
2. Ground consists of silty sand with alternation of sandy rich and clayey rich portions.
3. SPT values increases with depth from N=5-10 at the surface to N=50 at 40m in depth. The upper surface ground of 5-6m becomes weak in rainy season and hardens in dry season.
4. Ground water changes its level about 5-6m between rainy and dry season.
5. Top surface soil of 5m has strong effects on seasonal changes of weather.
6. The upper surface ground of 5-6m may not be reliable as a foundation of structures due to the effects of under ground fluctuation.

Samples from boring were tested and the results are as follows,

1. The top surface soil of 40m in the area is lateritic soil of silty fine sand and yellow to brown in color.
2. The main components of mineral are quart and kaolinite.
3. Natural water contents ranges from 10 to 20 % with pH=6 in average.

5.6 References

JSA(1995) Geotechnical Report, Annual Report on the Technical Survey of Angkor Monuments, published by JICE(Japan International Cooperation Center), pp.140-200

JSA(1996) Geotechnical Report, Annual Report on the Technical Survey of Angkor Monuments, published by JICE(Japan International Cooperation Center), pp.327-384.

6 Stability of Tower of Prasat Suor Prat

6.1 Prasat Suor Prat

Prasat Suor Prat, which means 'Tower of Rope Dancer' in Khmer, and some people believe that dancer had used to walk on a rope between the towers and make a performance in Royal Plaza in old days. There are 12 towers in the east end of the Royal plaza, which are divided into north and south group.

Photo 6-1 Prasat Suor Prat

In the north group, the six towers are named as N1, N2, --N6 from the center. N1, N2, and N3 towers stand near the North Pond, whose location is shown Fig.6-1. The south group locates at the opposite side against the Road to Victory Gate. The S6 tower has collapsed.
The inclinations of each tower were measured by the angle of wall against to vertical plumb lines.

Table-6-1 Several points were measured at different height of different wall for a tower.

	Inclination of Tower (in degree)			Inclination of Tower (in degree)	
Tower	East direction	North-direction	Tower	East direction	North-direction
N1	-3.,-2.9,2.8, -1.8, 3.0	3.5, 3.8, 6.6, 2.9, 2.8, 3.2	S1	0.5,0.8	-2.7,-3.4
N2	3.8,2.3,-1.8,3.0	1.7,3.2,1.4,1.9	S2	0.7,0.2	1.1,0.3
N3	2.8,2.6	2.5,0.1	S3	1.0,1.9	0.0,1.1
N4	0.6,0.8	0.5,0.0	S4	0.4,1.0	1.3,0.3
N5	1.2,1.3	2.0,1.3	S5	0.4,2.0	0.1,0.9
N6	-0.2,-0.5	0.2,0.5			

The results of the present inclination of these towers are plotted and shown in Fig.6-2.
It should be noted that the towers near the ponds shows much larger inclination than others and the directions of inclinations are towards the ponds. The inclination varies in a range from a few degrees towards Ponds. The S1 tower has inclined 2-3 degrees towards south direction. On the other hand, the

N1 tower has inclined towards north direction. The maximum inclination of 6.6 degrees to north is found for N1 tower.

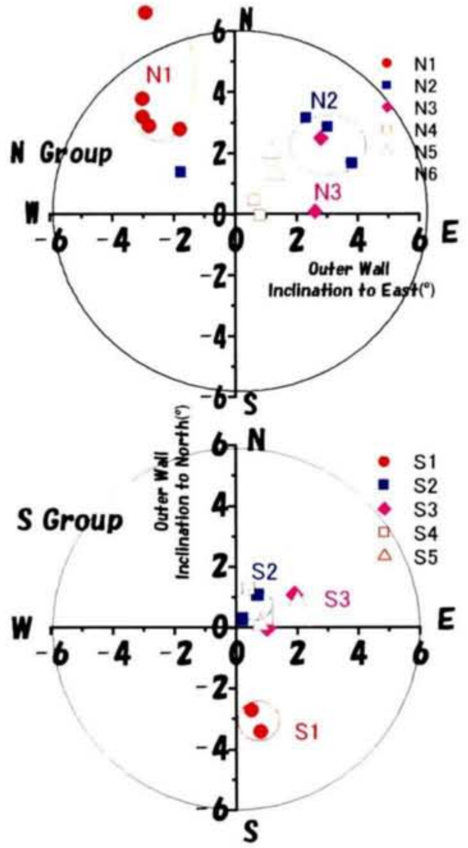


Fig.6-2 Distribution of Inclination of North and South Tower of Prasat Suor Prat

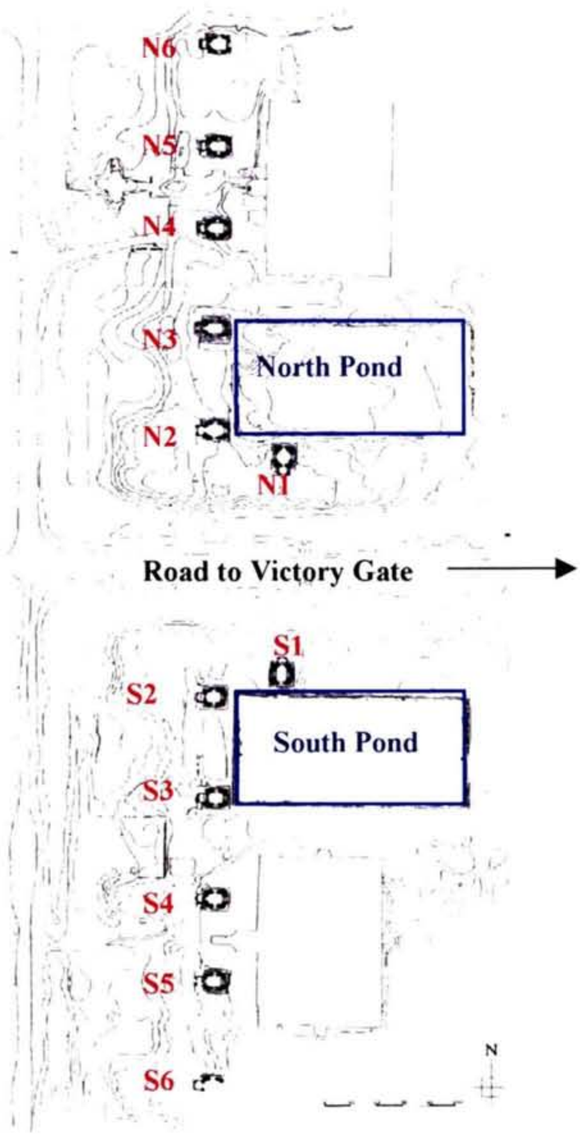


Fig.6-1 Prasat Suor Prat

JSA has selected N1 tower to work on its restoration. Geotechnical unit, JSA, has made efforts to characterize geotechnical aspects through measurements of the present states of deformed structures and monitoring of structure and ground behavior in a few years of period.

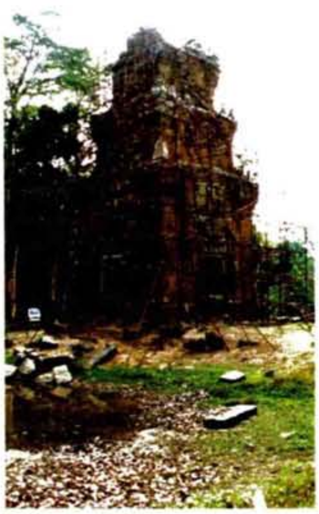


Photo 6-2 N1 Tower, Prasat Suor Prat and North Pond under dry season, February 1996

6-2 N1 Tower, Prasat Suor Prat

N1 Tower locates at the south of the North Pond of Prasat Suor Prat. The tower consists of mainly laterite blocks as main construction material. Sandstones were used at the entrance columns and lintels as well as decorative parts at each story

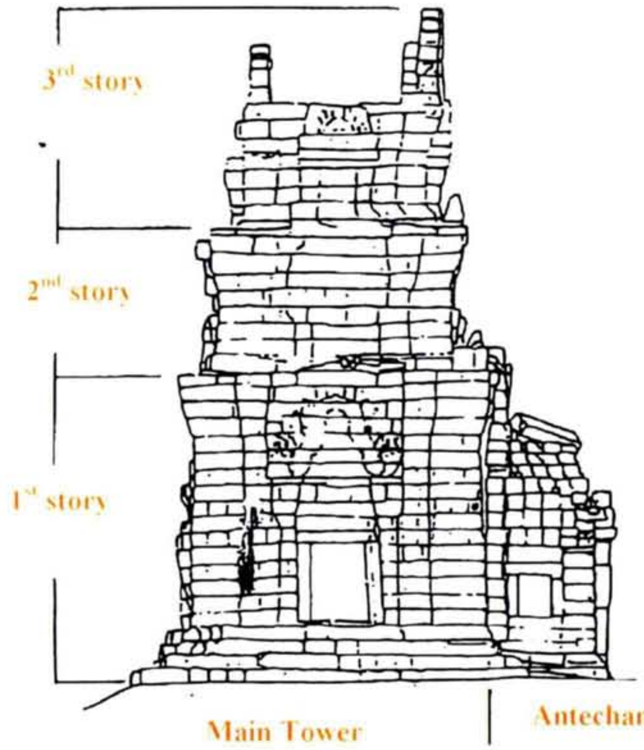
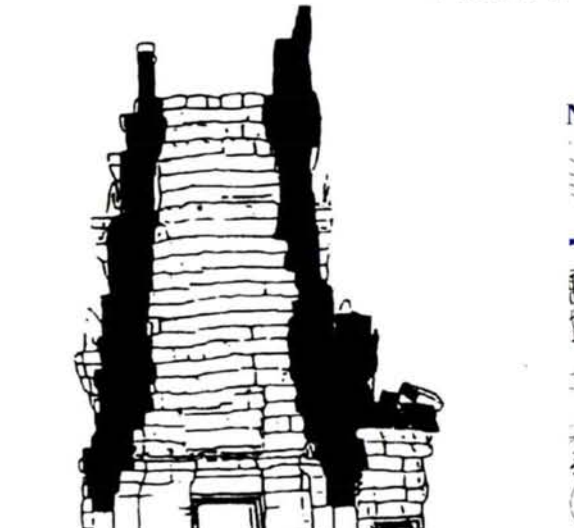


Photo 6-3 Side View of N1 Tower, Prasat Suor Prat



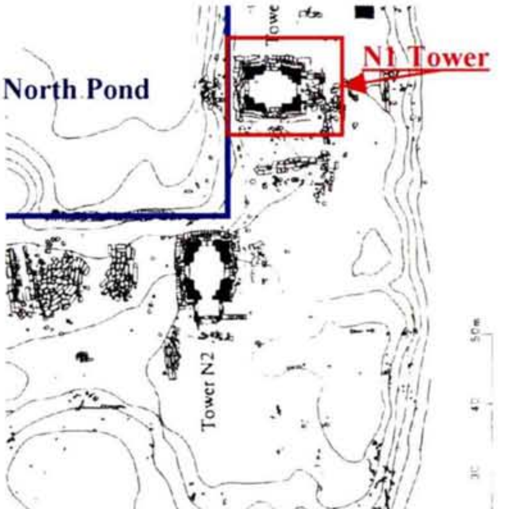
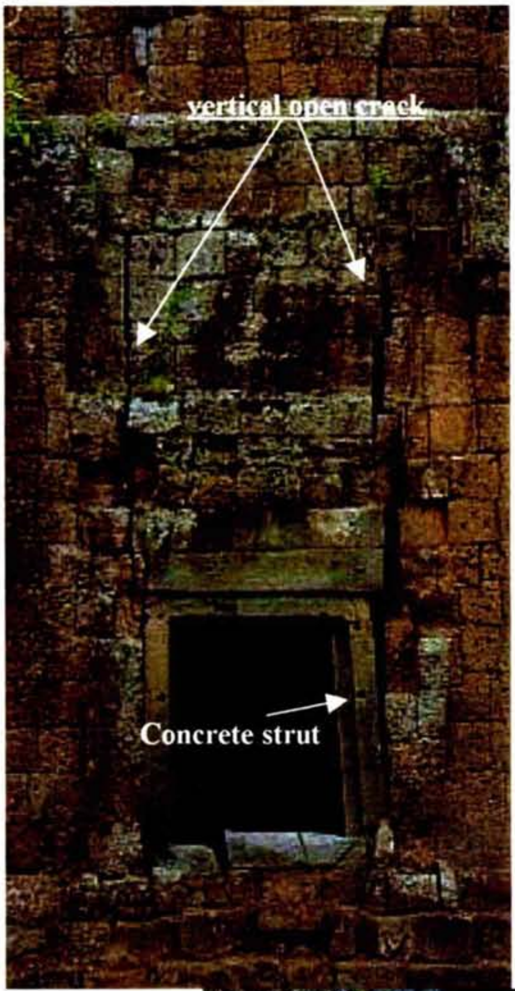


Fig.6-4 Location of N1 Tower

Fig. 6-3 Vertical Section of N1 Tower along NS

The width of the main hall is 8m by 9m. As shown in Fig.6-3, inside of the Tower is hollow space of 4m x 5m. Every Tower has a small chamber in front of the Tower (Antechamber).
One of the Khmer characteristics in architect is that they never use wedge arch structure.
In Photo 6-4, two vertical open crack lines are extending from the each ends of lintel to the upper part of the 1st story. Whole weight of the laterite blocks between two cracks is supported by the lintel, which transmits this heavy load to the vertical columns. The both ends of the columns are further supported by horizontal bottom frame of stone beam as shown in Photo 6-4.



The horizontal base beam and laterite blocks beneath the beam are enlarged in Photo9-5. At the base of the wall opening, there is a horizontal stone beam, whose dimensions are 60cm in width, 30cm in thickness, and 170cm in length. The side vertical columns stand at the both end of the horizontal beam. The beam has broken at its center due to bending failure and split into four peaces and the both ends subsided against the central part. If we look the laterite blocks beneath the beam, it becomes clear that the laterite blocks have not only subsided but also compressed due to the excessive vertical load through columns. The right hand side laterite has been compressed about 4-5cm, which resulted in settlement of the column and had caused the shear failure of the horizontal base beam.
The vertical openings were found beneath the cracked positions of the sandstones. These openings were likely to be caused by a failure mode of punching shear.

Photo 6-4 Vertical Opening above lintel

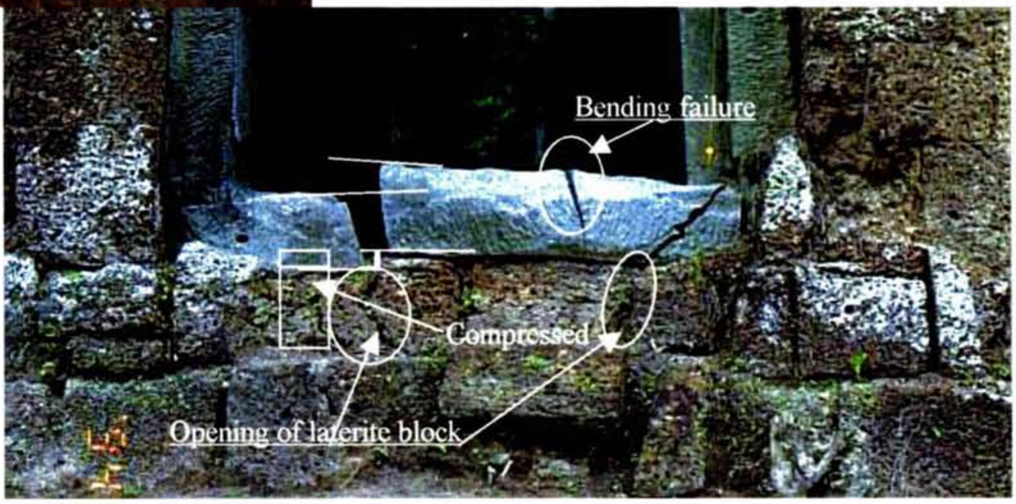


Photo 6-5 Compressed laterite block beneath horizontal beam sandstone

6.3 Deformation of Opening of Walls of N1 tower, Prasat Suor Prat

There are four opening space in each wall of Prasat Suor Prat. The lengths of the width of top and bottom are measured and listed in Table 6-2.

For any wall, the bottom parts of the openings are found wider than the upper part. The largest difference in the width is at west wall. The next is at north wall.

Table 6-2 Comparison among width of top and bottom opening at each wall

	width of the opening		difference in width
wall position	Top part	Bottom part	(bottom-top part)
east wall	170.3cm	182.0cm	12cm
west wall	171.3cm	185.0cm	14cm
north wall	168.0cm	178.0cm	10cm
south wall	124.0cm	131.7cm	7.7cm

Table6-3 shows the measured relative levels of the lintel of the opening at the center compared to that of the east wall and the relative level of top of the vertical columns within the opening for the same wall.

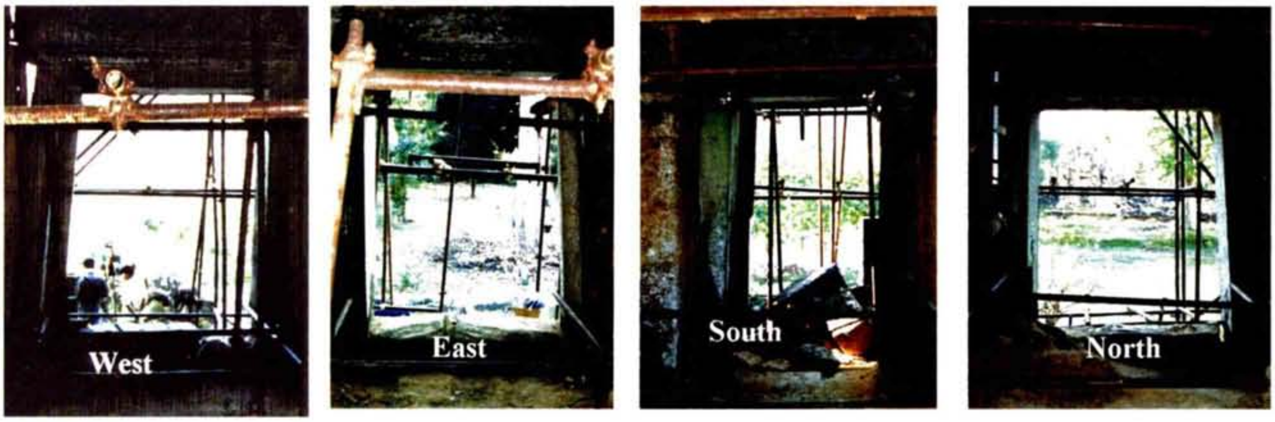


Photo 6-6 West, East, South, and North Wall from inside out direction.

Table6-3 Relative Level of Lintel of Opening to East Wall and Difference of Height of Base of Vertical Columns for each Wall

wall position	Relative level of the center of bottom of lintel to that of east wall	Difference of height of base of vertical columns for each wall difference/width
east wall	±0.0cm	−7cmN/182cm
west wall	−16.2cm	−15cmN/185cm
north wall	−28.2cm	−4cmW/178cm
south wall	−20.4cm	−1cmW/131cm

It is found that the opening at north wall is the lowest level among others. The north column of the west wall opening is also found the lowest among 8 columns.

The relative level of the center of each lintel is the maximum at north wall of 28.2cm to the east wall. However, it is not clear that the original level of each side of opening had been the same or not, no further discussion could be made.

On the contrast, the base beam stone of the Prasat Suor Prat was likely to have been laid horizontally, the present difference in the base of the both vertical columns on the same horizontal beam indicates the accumulated inclination in the past. At west and east wall side, the base of the vertical column shows 15cm and 7cm each towards north direction, which results in about 8.8cm/m and 4.1cm/m respectively. In north and south openings, westwards inclinations are identified as 2.3-0.8cm/m.

The above findings lead a conclusion that the tower is inclined mainly to the northwards.

6.4 Deformation of the foundation of N1, Prasat Suor Prat

Fig.9.4 shows plan view of N1 tower of Prasat Suor Prat at the foundation level. There are several steps made of laterite blocks surrounding foundation. The level of the surface of each step was measured and plotted in Fig.9-5 for west side of the N1 tower.

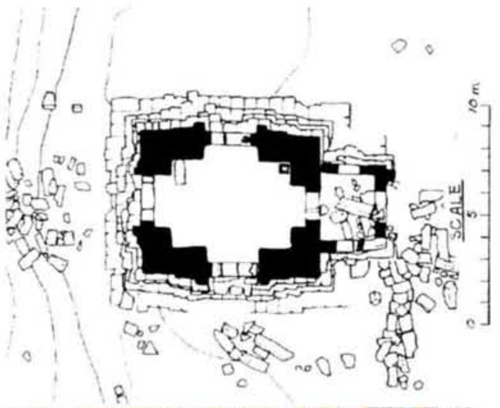


Fig.6-4 Plan view of N1 Tower at foundation level

Photo 6-7
West foundation

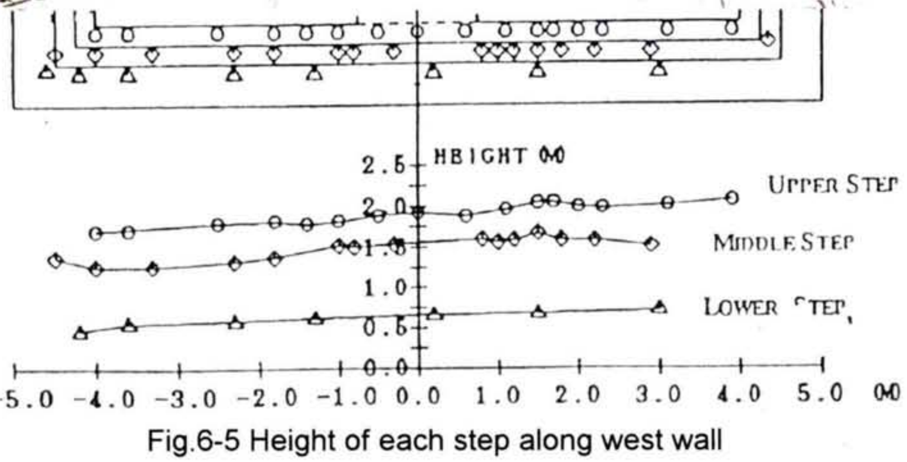


Fig.6-5 Height of each step along west wall

Photo 6-8
East foundation

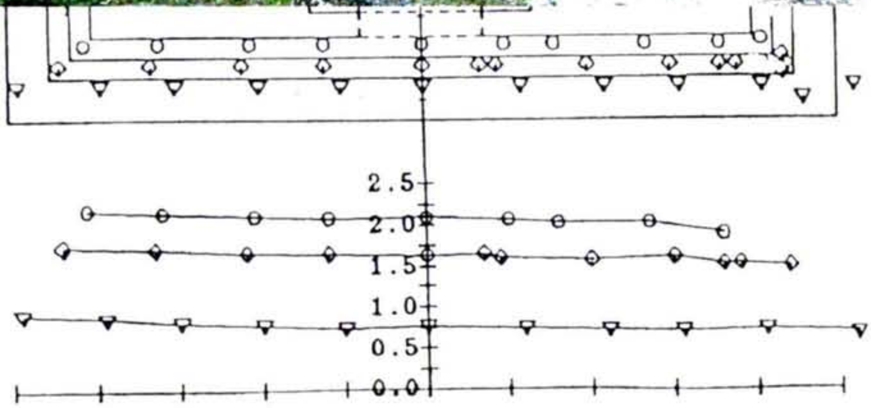


Fig.6-6 Height of each step of east wall

Fig.6-6 and 6-7 also show the height change of the steps for east and north wall. The northeast corner of the foundation was found the lowest level.

The maximum inclination of the foundation is north side foundation of about 40cm/10m, which is the same inclination direction as shown in Table 6-3. The inclination itself is one half of the inclination of the bottom beam of west opening.

Photo 6-9
North foundation

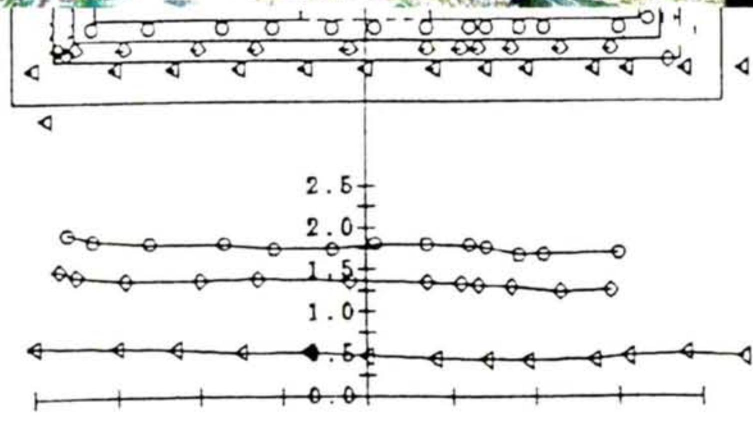


Fig.6-7 Height of each step of north wall

Based upon these measurements, the inclinations of north and westwards are evaluated and drawn as equi-contour line of relative settlement contour lines as shown in Fig. 6-10.

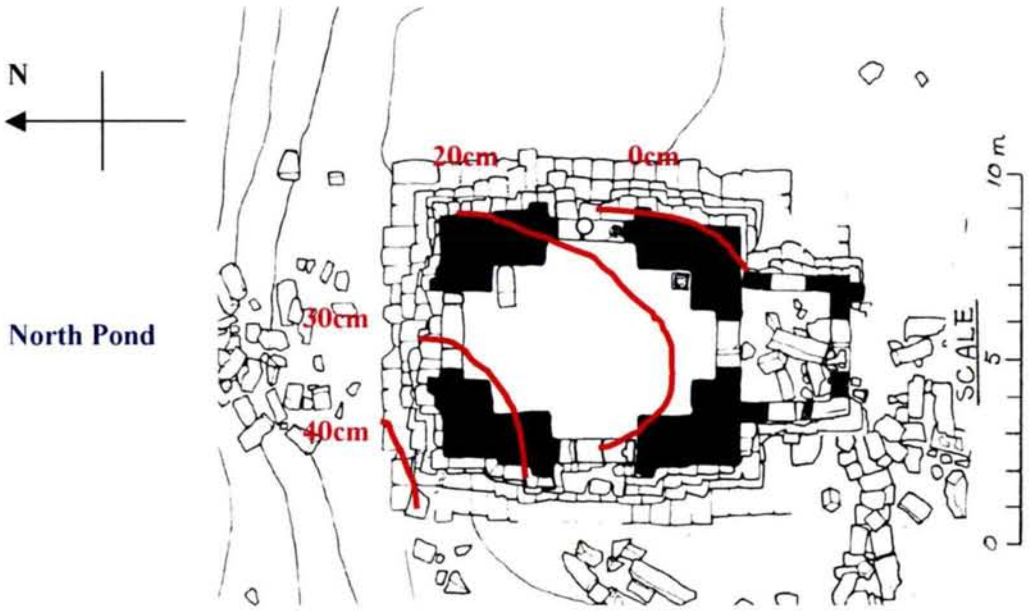


Fig.6-10 Estimated Relative settlement of N1, Prasat Suor Prat

6.5 Horizontal spreading of the foundation

The bottom widths of the opening of the each wall are shown wider than upper one. This may be due to horizontal spreading of the stones of the foundation. The characteristics of horizontal spreading may be studied by relative displacements of stone elements.

Magnitudes of opening of adjacent foundation stones of east and north face of N1 Tower are measured and the distribution of these openings is shown in Fig.6-11 and 6-12.

There are four levels of stone alignment and these are denoted U, M, L, and B from top to the bottom of the foundation. In each alignment, gap of opening of the adjacent stones are measured and shown in the figure. The approximate central position in horizontal of the opening in the north wall is also shown with vertical arrow (↓).

Any opening gap greater than 2mm is in block letter. The gap in any level shows larger value at the edges. At the base level, the large gap is found at the beneath of the edges of opening. This pattern of distribution of gaps suggests that the foundation is spreading horizontally, which have been caused by the ground movement beneath the foundation. The spreading portion of the grounds may be in the area where the larger stress had been concentrated by the tower structure. The deformations may be creeping characteristics in long term.

In Table 6-4, the gaps beneath the openings are summed for east and north sides, the total opening is about 10-18cm, which accounts for the difference between the top and bottom width of opening of the north wall.

This phenomenon of horizontal spreading of the foundation is confirmed at every faces of the tower except the south face, where the measurement is not possible. The horizontal spreading was caused by several reasons.

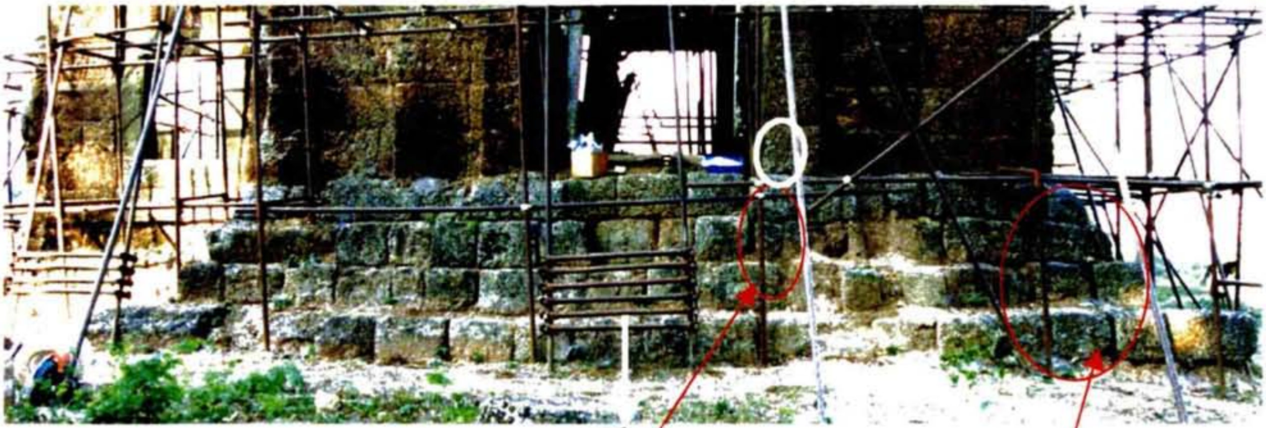


Photo 6-10 east foundation

(Center of the East side Opening)

← South North →

S3 S2 S1 0 N1 N2 N3 N4 N5 N6 N7 N8 N9 N10 N11 N12 N13

U	0	0	0	0.5	0	1	5.5	2	1.5	1	2	0	3	3	6.5	
M	0	0	0.5		0	1	5.5	2	1	5	2	?	1.5	8	2.5	5
L	?	0	0	2	0.5	0.5	1	1	?	?	?	0	1	5	5	
B		0	1	3	0.5	2	1	1	1	1	1	1	3	5	4	

unit in cm

U: upper level of foundation stones M: middle level of foundation stones

L: lower level of foundation stones B: base level of foundation stones

Fig.6-11 Distribution of Opening of adjacent stone elements (**East side**;N1)

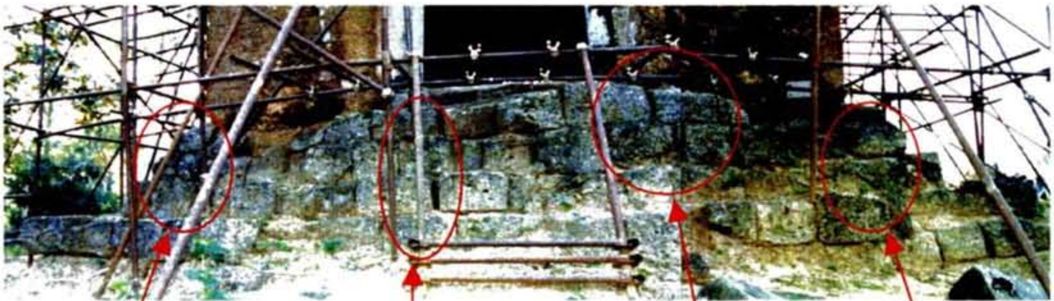


Photo 6-11
North foundation

(Center of the North side Opening)

← East ↓ West →

E9 E8 E7 E6 E5 E4 E3 E2 E1 0 W1 W2 W3 W4 W5 W6 W7

U	7	1	2	6	1	2	6	1	1	1	2	4	0.5	0	0.2	5
M		2	0.5	0.5	0.5	0.5	0.5	5	0.5	0.5	1	4	0.5	0.5	5	
L			0	0	0	0	2	7	0.5	1	3	?	?	?	2	
B	2	5	?	?	?	?	7	1	?	3	?	?	?	?	?	6

Fig.6-12 Distribution of Opening of adjacent stone elements (North side; N1)

Table 6-4 Comparison between spreading of foundation and widening of horizontal width of Opening

Wall location	East side	North side
Spreading of the foundation (sum of openings)	>10.5cm(sum from S3 to N6)	18cm(sum fromE4 toW4)
Widening of horizontal width (from Table 6-2)	12cm	10cm

The main cause might be due to horizontal outwards movement of compression of ground beneath the corner column where the load concentrated in long term. Wind force might have contributed to cyclic horizontal loading to the Tower, which additional horizontal displacements. The plant root intruded between laterite blocks had also widened the openings. The ground itself might have had expanded by some reason.

In the eastern face, there is a crack on east wall above an opening of stones in the upper level foundation. Since this crack is found rather fresh, the joint movement of the laterite blocks beneath the block might have caused the opening to begin and to continue to develop.

Photo.6-12 Fresh crack found at laterite block of East face (see Photo 6-10 white circle)

6-6 The horizontal spreading of foundations of other Towers

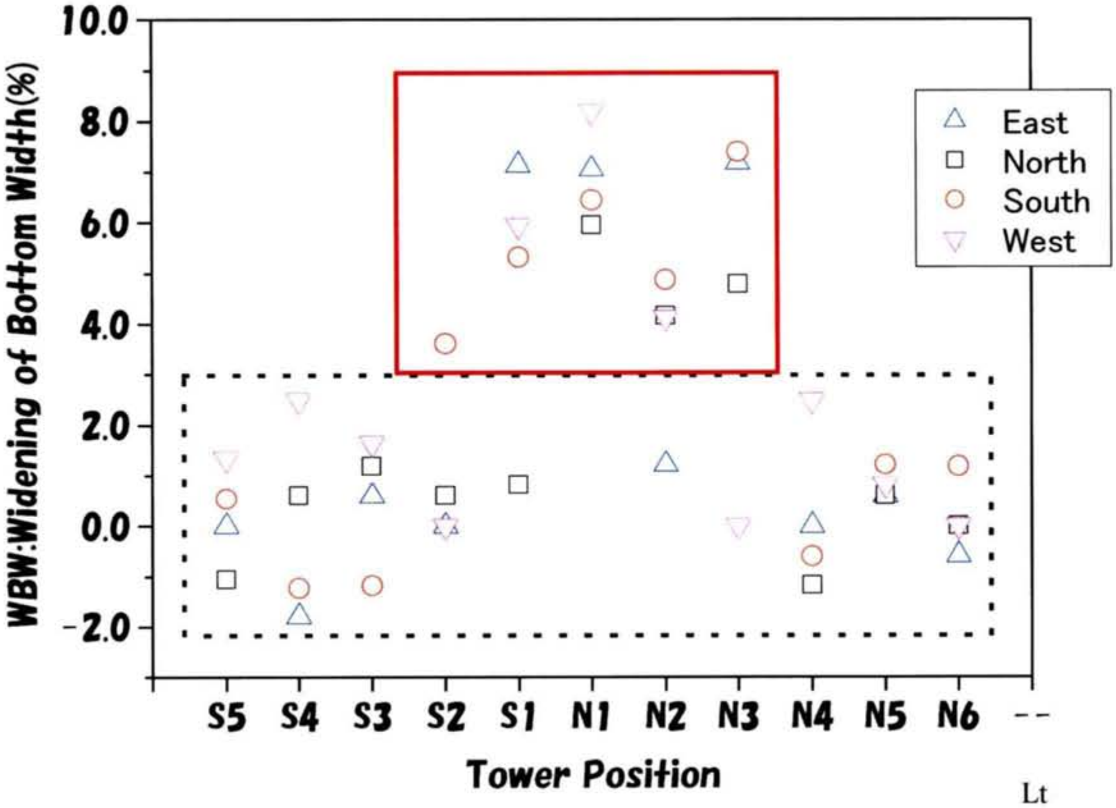
We extended the measurements of the bottom widening of open spaces as index of spreading of the foundations to other Towers.

Table-6.5 shows the inner widths of the bottom and top of the open windows, their differences, and the widening percentages of the bottom widths for all of 11 Towers except S6. These are plotted and shown in Fig.6-13. Among 11 Towers, they are divided into two groups. One is blocked within red color and another one is blocked in black color. The first group is characterized by the larger widening of the bottom width than the top. The larger values of the widening percentage of the bottom to the top are for N1 and S1 that are very near the Ponds. It is also found the same trend for N2, N3, and S2,

which are also nearby the ponds.
After the construction of the Towers, there were some differences of widths between the top and the bottom. Since it is found that there are some cases where the bottom widths are shorter than bottom ones, the original width may be within a variation of +−2.5% as shown in the black block in Fig.6-13.
There may be two different reasons of widened space. One is from mutual displacements among inner structure. Another is due to widening of foundation ground by some reason. Towers identified as wider bottom are N1, N2, N3, S1, and S2 and these Towers have a common condition that they stand nearby ponds.
Is there any reason for longer bottom width to top of the open window of the Tower near pond?

Table-6-5 Inner length of top and bottom horizontal beam of the open window, difference, and widened ratio

		Top	Bottom	Diff.	D/Top(%)			Top	Bottom	Diff.	D/Top(%)
S1	E	168	180	12	7.14	N1	E	170	182	12	7.06
	S	169	178	9	5.33		S	124	132	8	6.45
	W	168	178	10	5.95		W	171	185	14	8.19
	N	122	123	1	0.82		N	168	178	10	5.95
S2	E	168	168	0	0.00	N2	E	164	166	2	1.22
	S	166	172	6	3.61		S	164	172	8	4.88
	W	118	118	0	0.00		W	121	126	5	4.13
	N	167	168	1	0.60		N	168	175	7	4.17
S3	E	167	168	1	0.60	N3	E	167	179	12	7.19
	S	170	168	-2	-1.18		S	162	174	12	7.41
	W	121	123	2	1.65		W	124	124	0	0.00
	N	168	170	2	1.19		N	167	175	8	4.79
S4	E	168	165	-3	-1.79	N4	E	169	169	0	0.00
	S	163	161	-2	-1.23		S	169	168	-1	-0.59
	W	120	123	3	2.50		W	120	123	3	2.50
	N	167	168	1	0.60		N	170	168	-2	-1.18
S5	E	186	186	0	0.00	N5	E	168	169	1	0.60
	S	183	184	1	0.55		S	164	166	2	1.22
	W	149	151	2	1.34		W	121	122	1	0.83
	N	190	188	-2	-1.05		N	165	166	1	0.61
		(cm)	(cm)	(cm)	(%)	N6	E	170	169	-1	-0.59
							S	169	171	2	1.18
							W	121	121	0	0.00
							N	167	167	0	0.00



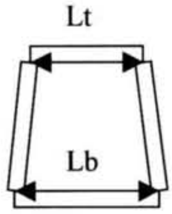


Fig.6-13 WBW: Widening of Bottom Width (%)

D=Lb-Lt
WBW=D/Lt

6-7 The displacement of embankment of South Pond towards pond

The embankment of the North Pond is badly damaged and the embankment in front of N1 Tower is failed. On the other hand, the embankment of the South Pond is kept in rather good condition; however, some displacement is observed along the north side embankment of the Pond.
The maximum horizontal displacement was measured as 40cm towards the pond. The horizontal point along the embankment corresponds to the structural center of the S1 Tower. It is expected that the vertical load by S1 Tower have resulted the embankment movement towards pond.

6-8 Deformation of the Towers and embankment of Ponds

The displacement of the north embankment of the South Pond is found almost symmetry against the centerline of the S1 Tower as shown in Fig.6-15. The right hand western side shows a little bit larger displacement than the left eastern side. The offset along the west embankment near S2 and S3 were not visible by naked eyes. The constraining condition for displacement of the embankment in three-dimensional effect may have contributed the little offset found in the west embankment of the South Pond. It might have also contributed the smaller deformation of the western side than the eastern side. This effect may be due the difference of plain-strain condition of the right of eastern side and the constrained condition of the western side by the west embankment. The N1 Tower might have had the same effect of the deformation of the south embankment of the North Pond, however, no further discussion is made due to no possible measurement on the North Pond.

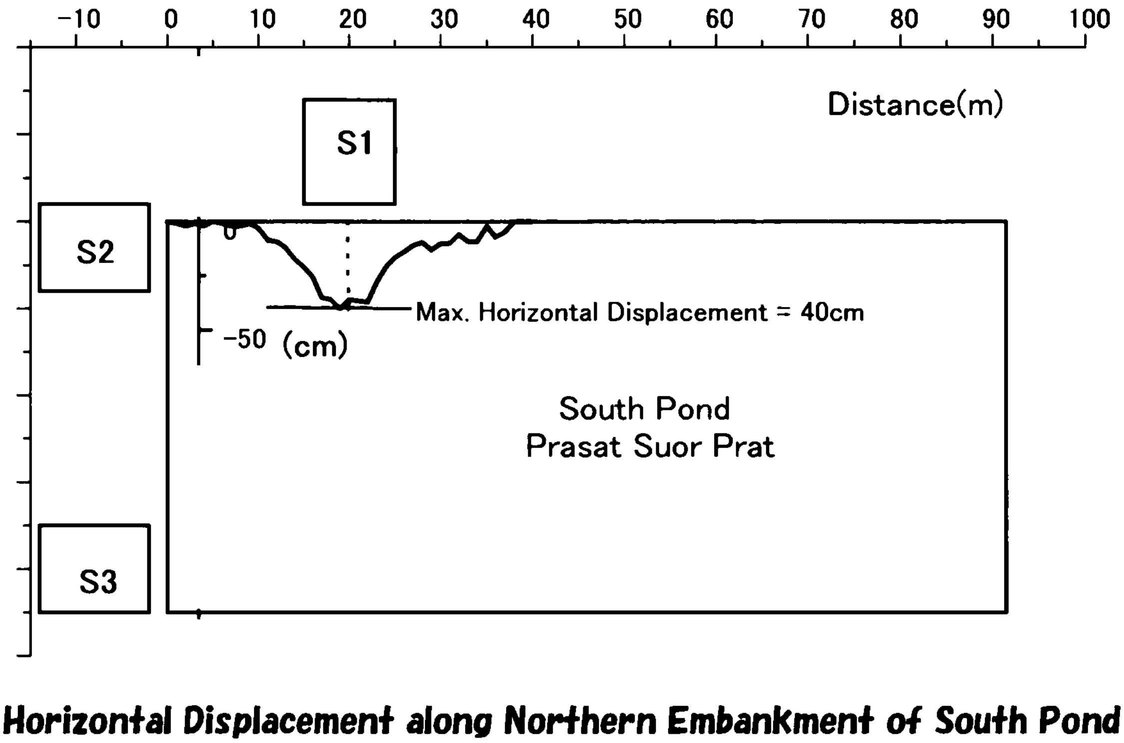


Fig.6-14 Displacement of the North side Embankment of the South Pond, Prasat Suor Prat

When the embankment displaces towards the pond, the ground behind the embankment becomes under extension state and widens in a direction of perpendicular to the embankment and inclines towards pond. Since the displacement is concentrated at the nearby tower, the ground along embankment expands in direction of embankment. These ground inclination and deformation causes tilting of the tower and spreading the foundation blocks that are observed for the Towers nearby Ponds. The largest displacement of expansion is expected in the direction perpendicular to the embankment, which is north-south direction for the both of S1 and N1 Tower.

This trend is confirmed by comparison of widening of bottom width of the open windows. The largest group of the widening is in the perpendicular direction of 7.1% in average, the second largest is in the parallel direction in front of the pond of 5.6% in average, and the smallest is parallel direction at the rear position of 3.6% in average as shown in Table 6-6. The widening of the east side foundation of N1 Tower shows smaller spreading of south side than north side, which corresponds to the expected larger extension of the ground at the nearer from the embankment.

As shown above, the tendency of the widening is in good sequential order to the expected ground deformation caused by the embankment.

The discussion of the absolute value of widening shall be discussed in future, however, it demonstrate the cause of tilting and widening of the Towers is due to a reason of the deformation of the embankment.

Table 6-6 Widening of the Bottom width of N1 and S1 according to Direction and Position

Direction		Position	Widening Ratio (%)	Averaged Ratio (%)
Perpendicular to Pond		N1 East	7.06	7.1
		N1 West	8.19	
		S1 East	7.14	
		S1 West	5.95	
Parallel to Pond	Front side	N1 North	5.95	5.6
		S1 South	5.33	
	Rear side	N1 South	6.45	3.6
		S1 North	0.82	

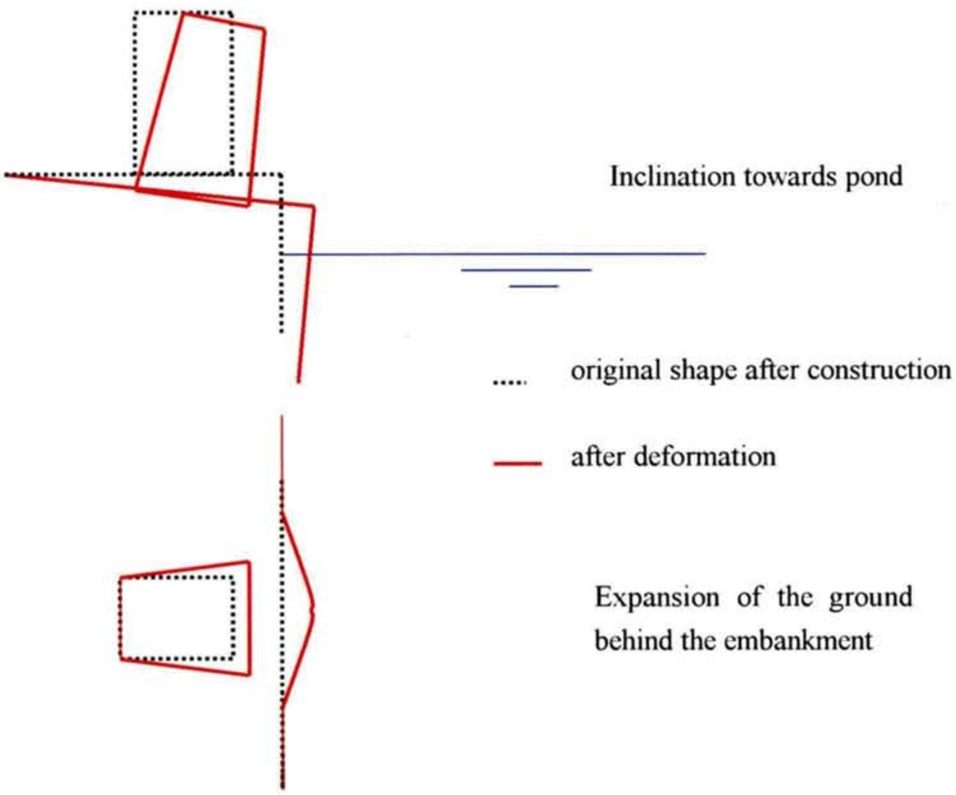


Fig.6-15 Schematic view of deformation of ground behind the embankment of pond

6-7 Geotechnical Monitoring at Prasat Sour Prat

Geotechnical unit, JSA, started to monitor ground behavior and structural response to the climate changed since 1997. Several kinds of sensors have been installed and data were collected.

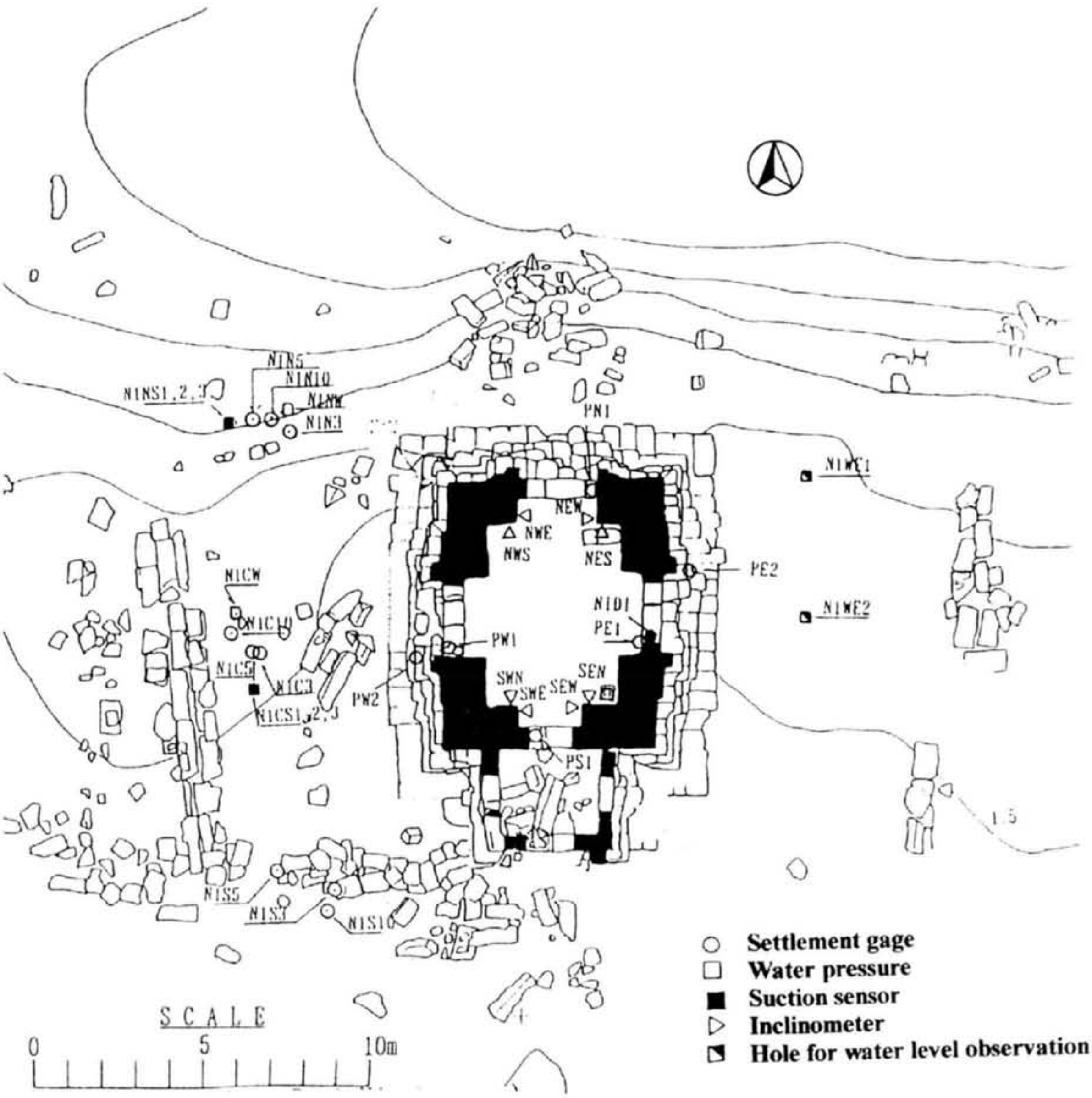


Fig.6-16 Location of Monitoring Sensors

These sensors include from basic metrological data of temperature, rainfall, to wind to structural behavior of gap between stone blocks and inclinometers as well as ground data of pore water pressure and ground settlement. The location of these sensors is shown in Fig.6-16.
The sensors are listed in Table 6-4.

Table 6-7 Instrument /settlement, suction, inclinometer, and water level Gages

Settlement gages			Suction gages		
Sensor I/D	**Position**	**Depth**	**Sensor I/D**	**Position**	**Depth**
N1N3	North point	GL-3m	N1NS1	North point	GL-1m
N1N5		GL-5m	N1NS2		GL-2m
N1N10		GL-10m	N1NS3		GL-3m
N1C3	Central point	GL-3m	N1CS1	Central point	GL-1m
N1C5		GL-5m	N1CS2		GL-2m
N1C10		GL-10m	N1CS3		GL-3m
N1S3	South point	GL-3m	N1SS1	South point	GL-1m
N1S5		GL-5m	N1SS2		GL-2m
N1S10		GL-10m	N1SS3		GL-3m

Inclinometer			Underground Water Level	
Sensor I/D	**Position**	**Wall face**	**Sensor I/D**	**Depth**
NE_W	NE column	west side wall	N1_NW	GL-10m
NE_S		South side	N1_CW	GL-10m
SE_N	SE column	North side		
SE_W		West side	N1_WE1	GL-10m
SW_N	SE column	North side	N1_WE2	GL-10m
SW_E		East side		
NW_E	NW column	East side		
NW_S		South side		

Photo 6-13 Vertical inclinometer installed at walls inside N1 Tower, Prasat Suor Prat

Photo 6-14 Settlement Gages at N1 Tower, Prasat Suor Prat

6.8 Inclination characteristics of N1 Tower based upon monitored data

We set inclinometers on the surface of columns at inside corners in the main room of N1 tower, Prasat Suor Prat, and started monitoring since February 1997. There are four laterite block columns at every corner of the inside of the N1 tower, each of which has two faces.

We have installed eight inclinometers for each wall face as shown in Photo 9-13. Each sensor was named as the relative position of the column and the direction of the face where the inclinometer was installed. If the sensor is installed on the east side face of NW corner, then the sensor is named as NW-e. Measured value is shown in mm/m. The sensor NW-e measures inclination of wall in north and south direction. If the wall face inclines clockwise, the change of the data is shown plus. The plus change of NW-e sensor indicates the inclination of NW wall to the north. The plus change of NE-w sensor indicates inclination of NE wall to the south. To avoid some confusion, the data were converted to show plus change as the inclination to north and east directions. Photo9-14 shows settlement gage at west of N1 Tower. Photo 9-15 shows wind and rain monitoring near N4Tower, Prasat Suor Prat.

Photo 9-15 Meteorological monitoring near N4 Tower, Prasat Suor Prat

6.8.1 Daily change of Inclinometer

We will discuss the daily change of inclination at first. Fig.6-17 shows inclination data of two and half days from February 3 to 5 of 1997. During this period, we selected the sampling interval as one minute and we will discuss some character of errors of the measured data. In the Fig.6-17, the upper four figures are inclination change of the corner walls and the bottom is temperature change at the

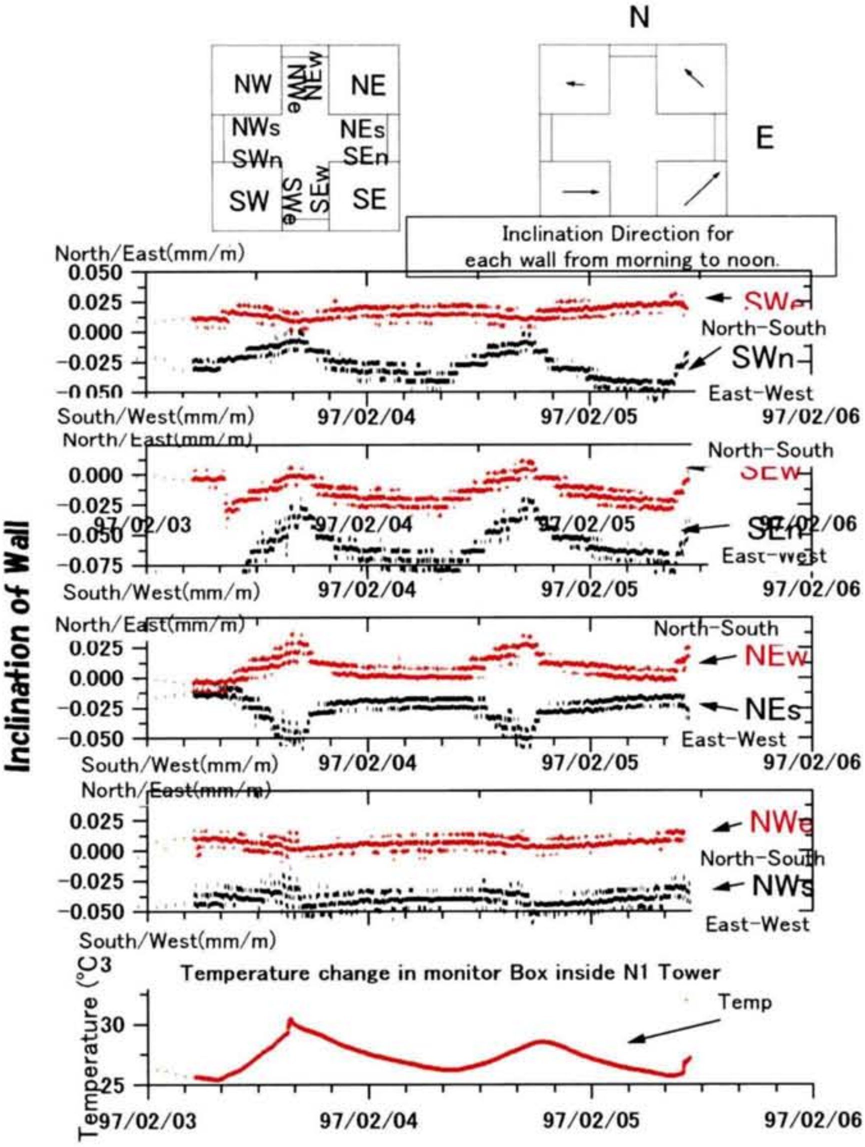


Fig.6-17 Daily change of inclination of wall inside N1 Tower, Prasat Suor Prat

monitoring box at the SE wall inside the main room.

The temperature shows its minimum at about 8 o'clock in the morning and its maximum at 7-8 o'clock in the evening. The temperature measured inside might be delayed compared to outside of the tower.

The smallest unit of inclination readout in digitization is about 0.008mm/m. The inclination data were scattered within ±0.02mm/m(=3seconds) of the error specified by the maker of the sensor.

6.8.2 Maximum daily change of inclination

The maximum daily changes for each four columns were found 0.01-0.05mm/m with the maximum for SE. The minimum daily change was less than 0.01-0.02mm/m at NW corner, however, the other corner shows two to three times larger. These daily changes are caused by temperature effect and the northwest corner was the minimum affected by temperature change in a day.

Table 6-8 Daily Change of Inclination(February 4,1997)

Wall	SW corner		SE corner		NE corner		NW corner	
Wall face	East	North	West	North	West	South	East	South
Inclination direction	NS	EW	NS	EW	NS	EW	NS	EW
	mm/m	mm/m	mm/m	mm/m	mm/m	mm/m	mm/m	mm/m
Daily change	0.01	0.04	0.03	0.05	0.03	0.03	0.01	0.02

6.8.3 Daily change characteristics

We found several characteristics of the hourly response during a day in Fig.6.17.
In the morning, the inclinations of the corner columns increase with time until about P.M.4, when it reaches the maximum. The columns of SW and SE begin to incline first at 8 A.M. followed by NE at 10A.M.and lastly NW at 12A.M. After reached the maximum at 5-6 P.M., on the contrary, NE is the first to move back compared with SW and SE columns.
After 5-6 P.M., every column begins to decrease its inclination until the next morning. The rate of inclination change decreases with time and becomes much slower after 8 P.M.
Table 6-9 shows these characteristics of each column. Fig.6.17 also shows vector display of the inclination direction of each column from the morning to the evening. If the tower is considered as a solid structure, the inclination should be the same for every part in the structure. The different amount of inclination for each column means the each column behaves independently. Structurally, these four columns are connected and should be affected each other.
The behavior of inclination tower is considered related with the effect of sunshine on the structure. The NE column inclines towards northwest because of the expansion of the east-south expansion by the increase of temperature by the sunshine. SE column inclines towards NE direction because of the expansion of SW side.

Table 6-9 Hourly Change of Inclination

Wall	SW corner		SE corner		NE corner		NW corner	
Wall face	East	North	West	North	West	South	East	South
Time of response	AM8	AM8	AM8	AM8	AM10	AM10	AM12	AM12
Time to reach the Max.	PM5	PM5	PM5	PM5	PM5	PM5	PM6	PM6
Inclination direction	S+	E++	N++	E++	N++	W++	S	W

On the other hand, SW column inclines towards eastwards and southwards, and NW inclines towards westwards with a small amount. This movement is difficult to explain by some simple mechanism based upon the present knowledge.
Even though it may be necessary to analyze and to understand these mechanical behavior, we can conclude by the observation that the tower itself does not behave as a solid structure but moves independently for each corner column interacting each other.

6.8.4 Annual change

Figs.6-18 and 6-19 show the inclination data of the Prasat Suor Prat for two years. These data, when the data were failed to retrieve, were skipped out. For some components like SEw the measured data shifted abruptly, which is considered due to repairing works of wire connection. These movements is difficult to understand, however, because of no significant change of other inclinometers and no meteorological change corresponding to this events, it is assumed as a meaningless phenomena.

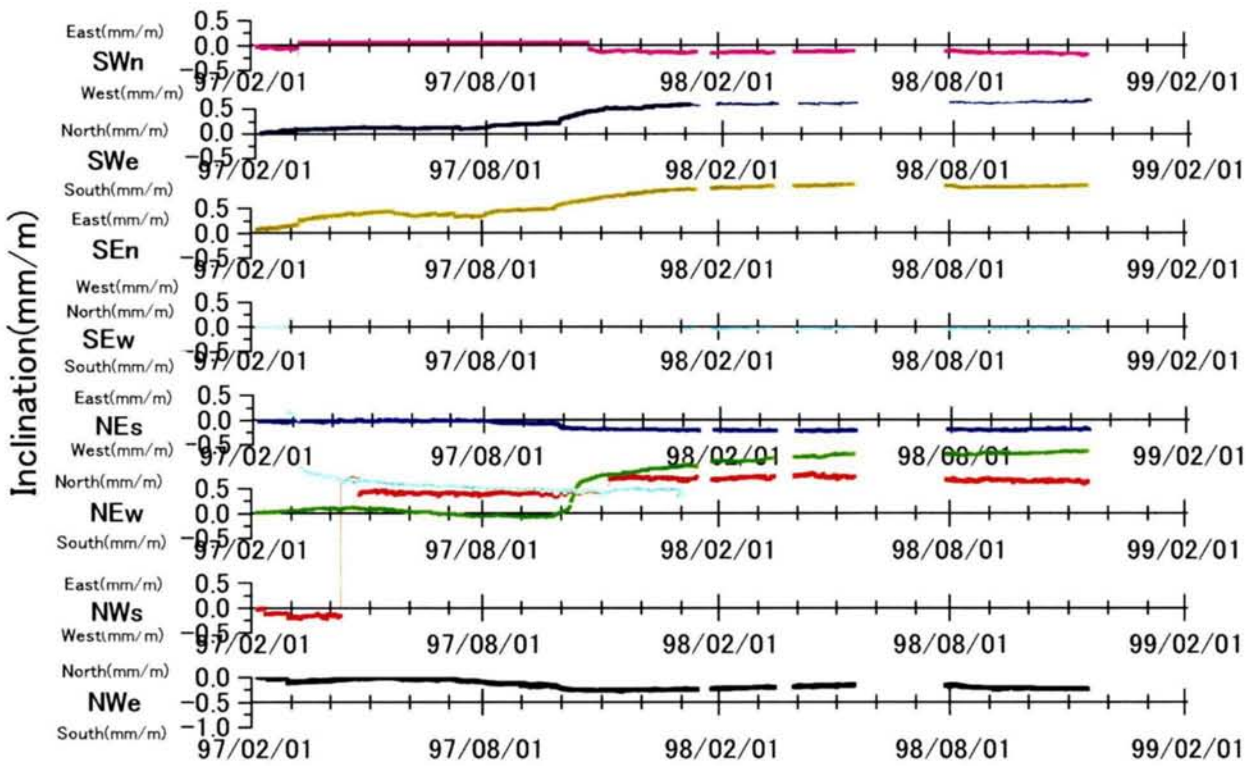


Fig.6-18 Inclination of stone column inside of N1 Tower, Prasat Suor Prat

In fall of 1997 there was a heavy rain when the embankment of moat near the west gate was failed at Angkor Wat. The inclinometer of N1 tower of Prasat Suor Prat had recorded movement of the tower caused by this rain. The inclinometer record of Fig.6-18 indicates the movements of the four walls as follows,
NE column; inclination towards NNW
NW column; inclination towards SW

SE column; inclination towards N
SW column; inclination towards N

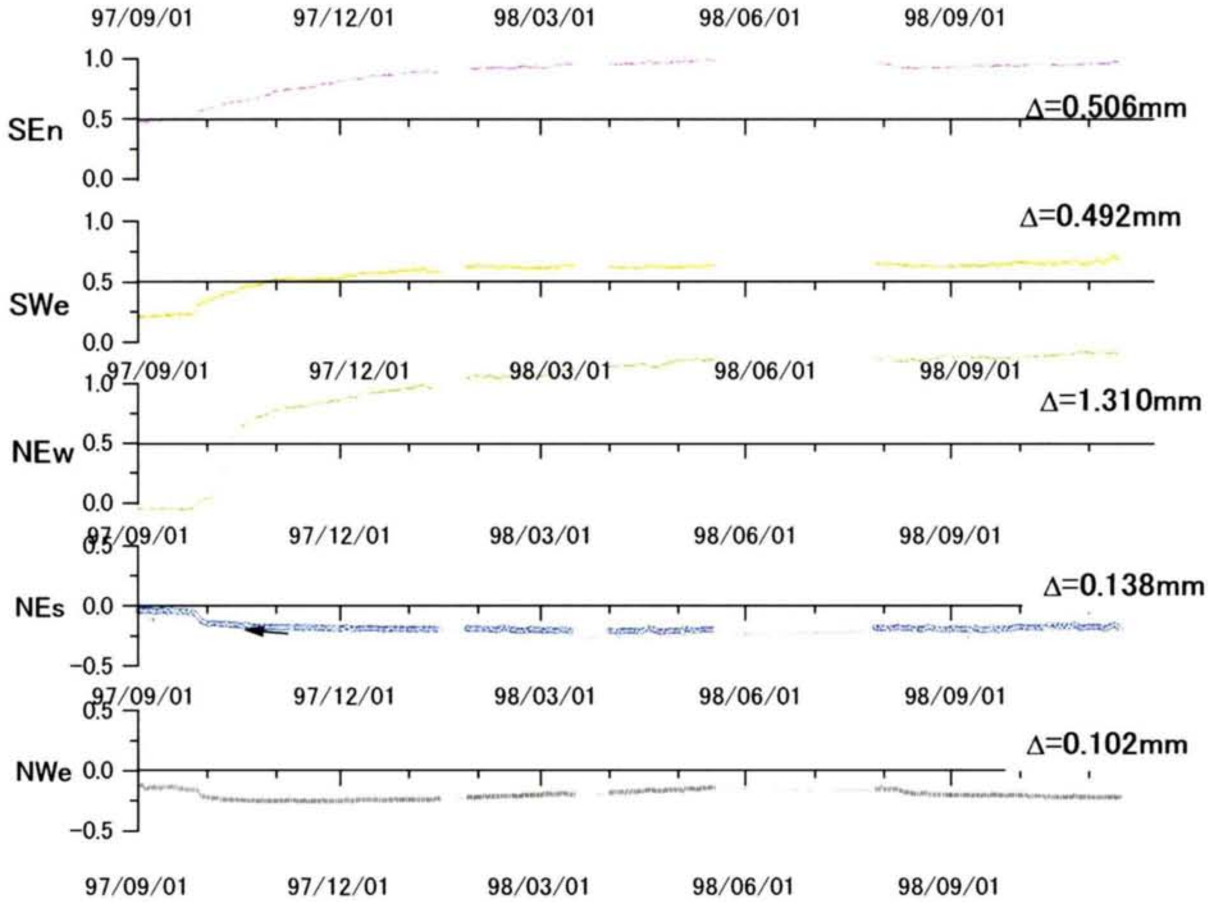


Fig.6-19 Creep of Inclination of Inside Column o N1 Tower, Prasat Suor Prat

The movements continued for more than several months. In Fig.6-19, five components among eight inclination records were selected and shown to see how the inclination increased after the event had been triggered from September 1,1997 to November 16,1998

Table 6-10 Creep Change of Inclination of Wall of N1, Prasat Suor Prat after Heavy Rain

(mm/m)

Wall	SW corner		SE corner		NE corner		NW corner	
Wall face	East	North	West	North	West	South	East	South
97/09/01 3:00	0.207	0.067	-3.289	0.470	-0.054	-0.041	-0.125	2.295
98/11/16 3:00	0.699	-0.178	-0.038	0.976	1.256	-0.179	-0.227	2.530
Due to creep	0.492			0.506	1.310	0.138	-0.102	
Other than creep		-0.245	3.251					0.235
Inclined Direction	N	—	—	E	N	E	S	—

. The largest movement was taken place at west wall of NE column (NEw) where the rate of change right after triggered 0.1mm/m/day and gradually decreased about one tenth after ten days

. The creeping movement continued for almost a year. Columns of SW, SE, and NW showed much smaller movements and the same character of long-term creep as NE column.

The inclination changes of each columns from 97/09/03:00 to 98/11/16:03:00 are listed in Table6-10.

The maximum creep inclination observed was 1.3mm/m of NE column in northward direction. In

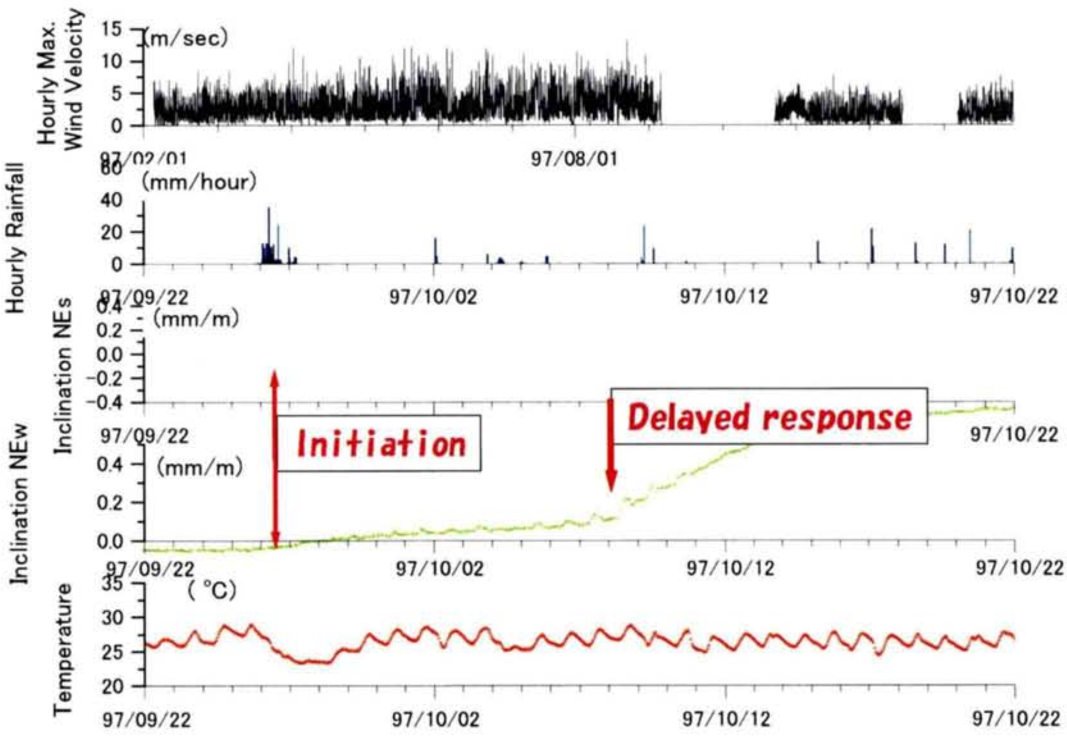


Fig.6-20 The Initiation of creep

1998, there have been neither creep event nor sudden large change comparable with this amount.

The present absolute inclination of N1 tower is about 40mm/m, which means that 30times larger than the inclination changes comparable to the 1997 event. We have not confirmed yet the specific mechanism of this event. However, the inclination change was due to foundation/soil system and/or upper structure of the tower itself.

We discuss the mechanism based upon the records of ground settlement monitored at the same time in the following section.

Fig.6-20 shows the initial process of creep to start. It is of a great interest to see there is some delay of about 10days between the initiation of change and the delayed response time of creeping.

6.9 Settlement/Heave based upon monitoring

Fig.6-21 shows the results of monitored ground settlement near N1 tower as well as rainfall and temperature change. The settlement was measured at three points of north, center, and south along a N-S line that is about 8m apart from center of N1 (see p.314, JSA Report 1997). North and south points are located at the extension lines of north and south edges of front room of the tower. Center point locates at the middle between the north and the south points. At each point, three different settlement pipes of three, five, and ten meter in length have been installed, which measures shrinkage or heaving between the ground surface and three different depths. Fig.6-21 shows the monitored results from February 1997 to November 1998 with a lack of data in summer 1998.

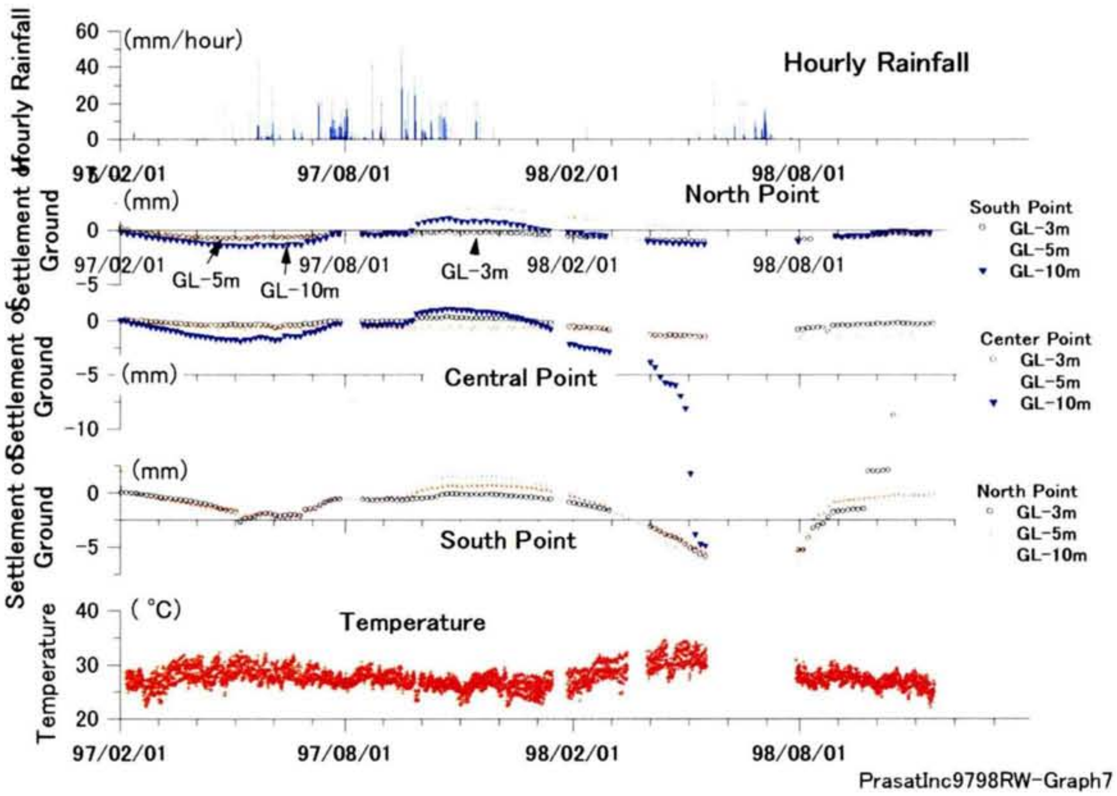


Fig.6-21 Settlement vs. Rainfall and Temperature at west of N1 Tower, Prasat Suor

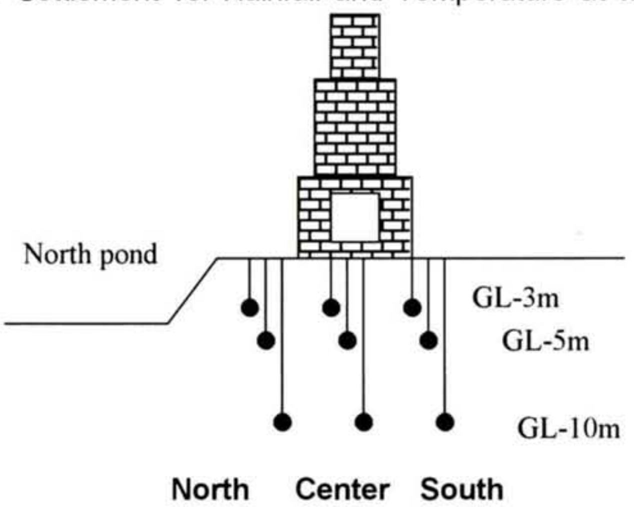


Fig.6-22 Settlement Gages

Settlement/heaving characteristics based upon the monitored data in the last two years are summarized as follows,

In dry season of 1997, the ground settlements of about 1-2mm were observed from February 1 to May 1, 1997.

After May when the rainy season starts, the settlement stops and heaving takes. The north point shows the largest settlement and swelling among three monitoring points. The settlements became rather stable during rainy season from August 1997 before the end of September when the heavy rain occurred. They have been activated due to the heavy rain that had caused the swelling of the ground. There are some common characteristics of these three points. In each point, the heaving from the ground surface to the shallowest 3m depth is almost negligible. However, the deeper points of 5m and 10m show much larger heaving after the heavy rain. This suggests that the water had infiltrated into the deeper layer, which became to expand to swell.

In November 1998, the beginning of next dry season, the ground showed some recovery. After one year from February 1997, the ground had shown to return to almost the same level as before.

The maximum changes of ground settlement and swelling at three monitoring points are 3-4mm with an average of 2.13mm. After one year from 97/2 to 98/2, the maximum settlement residual is 2mm with an average of 0.39mm. It should be noted that the settlement during the later part of dry season showed about three times larger than the same period in the previous year of 1997, which may be due to rather high temperature in 1998 compared to those in 1997, which are also shown in Fig.6-23. Characteristics of settlements or swelling along the depth shall be treated in the next section.

6.9.1 Settlement and swelling of the ground

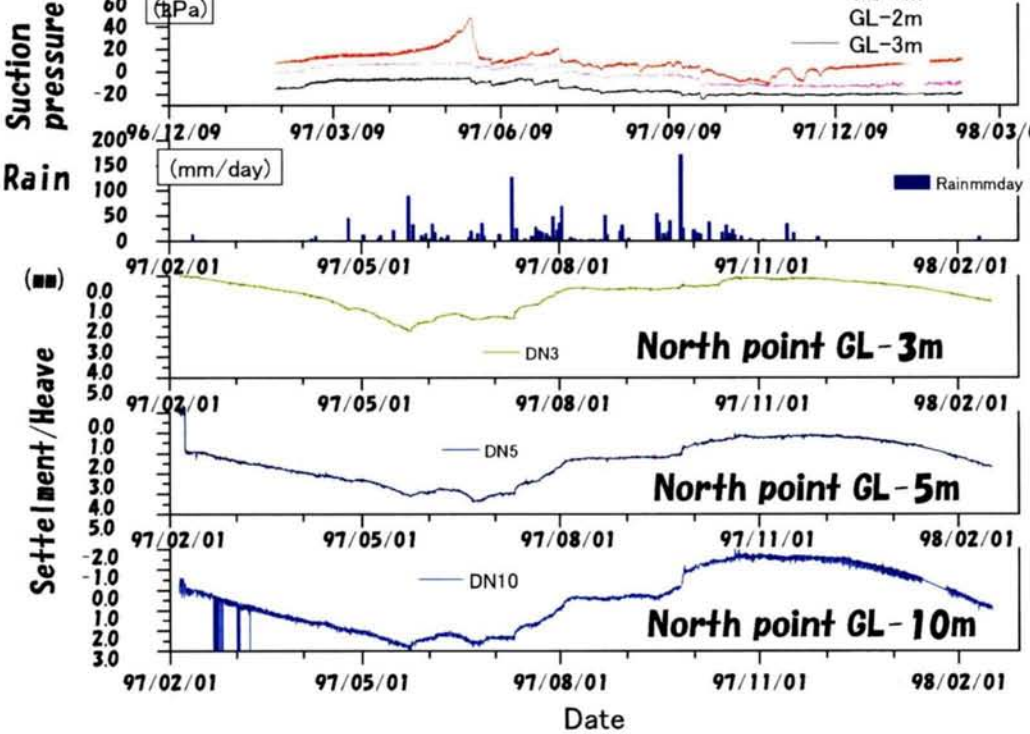


Fig.6-23 Suction, Rain, and Settlements

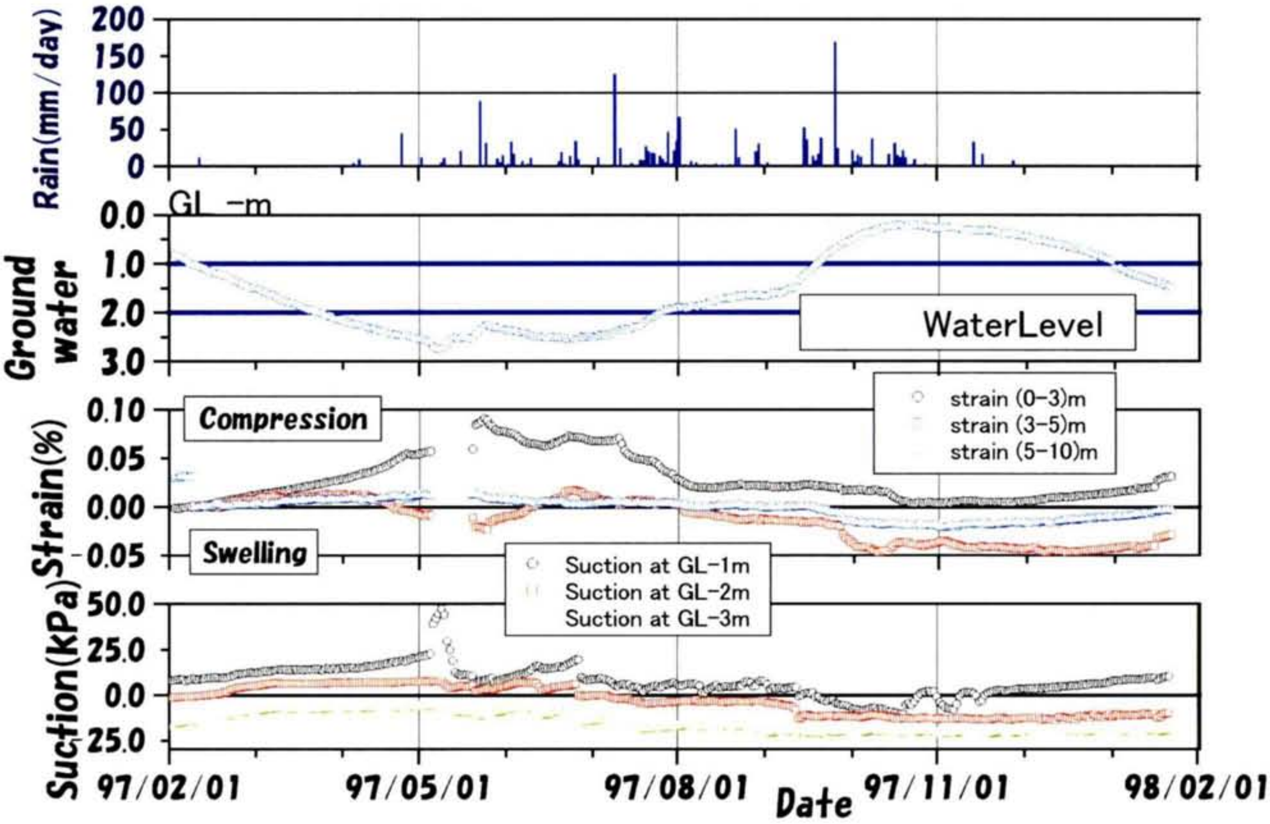


Fig.6-24 Rain, Ground Water, Strain of the Ground, and Suction

We have also installed suction pressure sensor near settlement gages at depths of GL-1m, GL-2m, and GL-3m.

The monitored results of suctions at north point are plotted in Fig.6-23 with rainfall and settlements.

Suction pressures increased with time in dry season from February to April 1997 and began to decrease in May when rainy season started. The suction pressure at GL-1m shows the largest value among three depths.

It should be noted that the settlements and swellings are closely related with each other. The shrinkage of the ground continued when the suction pressure increased until the suction began to decrease.

Fig.6-24 shows time histories of rain, ground water level, vertical strains, and suctions at north point. Vertical strains are computed by the differential settlement between GL-3, GL-5, and GL-10m divided by corresponding distances.

In dry season from February 97, suction pressure at GL-1m increased which corresponds the dewatering of underground water level. The compression of the ground from GL to GL-3m is found also increased.

Fig.6-25 shows the relationship between ground water level and suction pressure for three depths of GL-1m, GL-2m, and GL-3m. All three suction pressures have strong relationship between ground water levels. When the ground water level decreases, the suction pressure increases.

The suction pressure installed at GL-1m showed sudden increase of the pressure when the ground water level decreased about GL-2.5m.

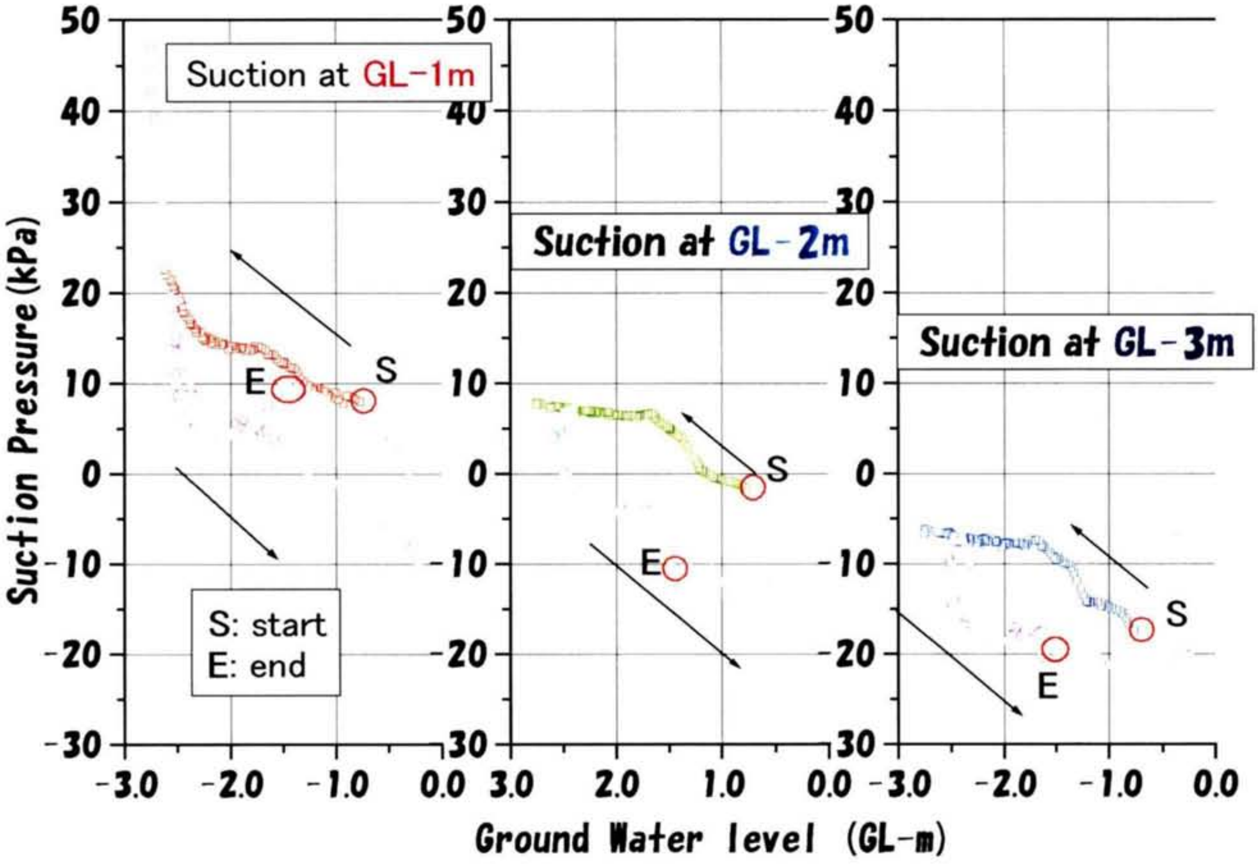


Fig. 6-25 Ground water level vs. Suction pressure

Since the ground water level has varied from GL-0.8m to GL-2.5m, suction sensor at GL-3m was considered as under the ground water level and the measured values are negative, which indicates the suction pressure has disappeared and pore pressure was build up. However, the pore-pressure responds with ground water with hysteresis. This may be due to unsaturated states of ground. Overall responses of suction pressure against change of water level are found about 10kPa per 1.0m.

Fig.6-26 compares vertical strains with ground water level and suction pressures. In general, the change of underground level induces the effective stress on the soils in the ground, which results in volume change of the ground.

Based upon Fig.6-26, the compressibility of the ground may be computed for each layer as follows,

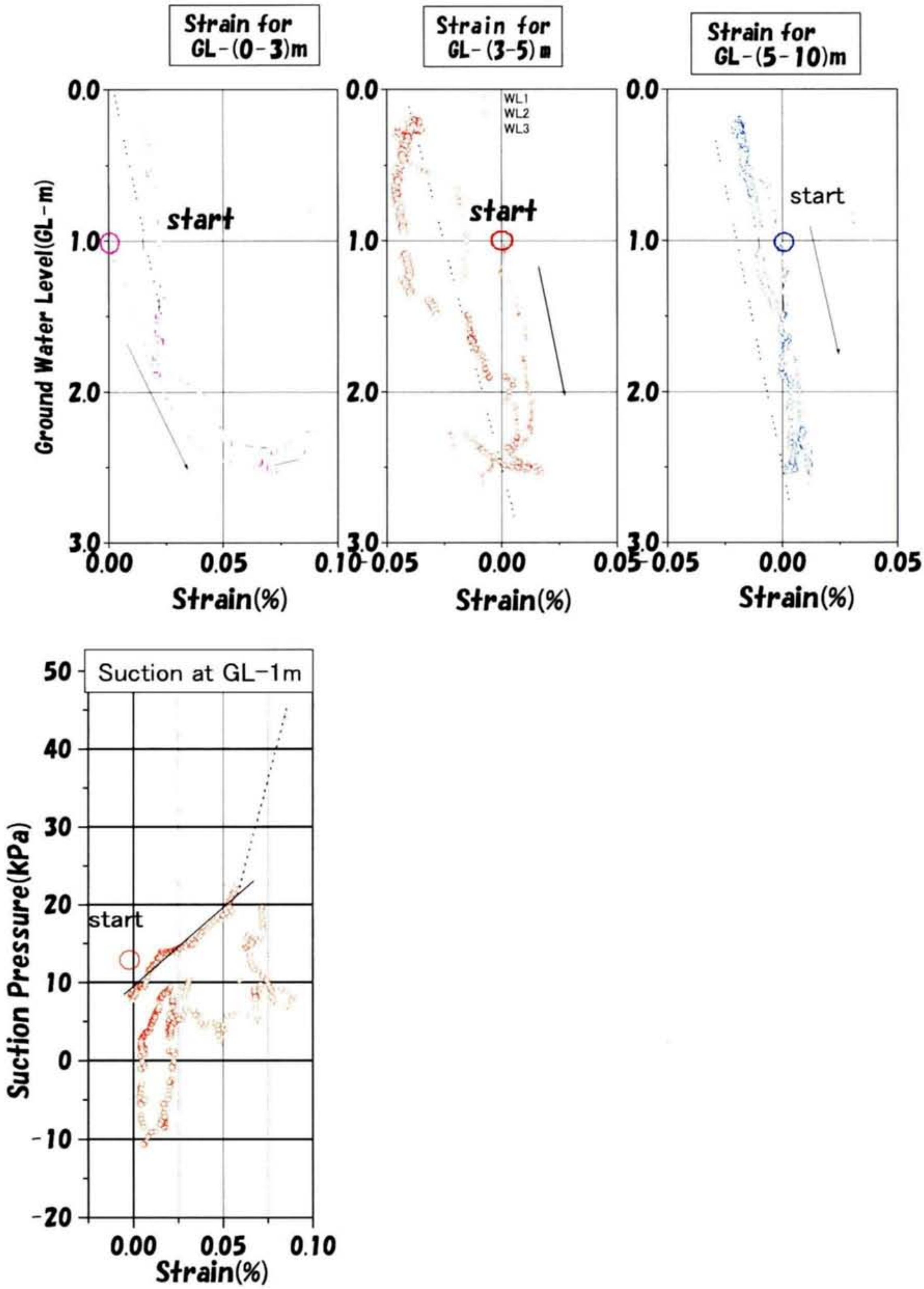


Fig.6-26 Vertical strain, Ground Water and Suction Pressure

Table 6-11 Compressibility estimated from field monitoring

	GL-0m to GL-3m	GL-3m to GL-5m	GL-5m to GL-10m
m_v from Change of Water level	0.025MPa^{-1}	0.017 MPa^{-1}	0.0125 MPa^{-1}
m_v from Suction	0.025 MPa^{-1}		

The compressibility was found to increase with the depth. The apparent compressibility from effective stress change caused by water level and suction change were obtained as the same value of 40MPa.

If the water table is lowered by 5m or 10m in the future, the settlements from the direct change of effective stress are estimated as follows.

Table 6-12 Settlement anticipated by de-watering

	settlement	GL-0m to GL-3m	GL-3m to GL-5m	GL-5m to GL-10m
		40MPa	60MPa	80MPa
Expected strain for 5m change(50kPa)	8.45mm	0.125% =3.75mm	0.083% =1.6mm	0.063% =3.1mm
Expected strain for 10m change(100kPa)	16.65mm	2.5% =7.25cm	1.66% =3.2cm	1.23% =6.2cm
2.5m	4.1mm	0.06% =1.8mm	0.04% =0.8mm	0.03% =1.5mm

The settlement caused by suction stress should be added with the above settlements. If the suction stress is equal to the amount observed by the monitoring, 25kPa may be assumed.

Table 6-13 Settlement anticipated by suction

	settlement	GL-0m to GL-3m	GL-3m to GL-5m	GL-5m to GL-10m
		40MPa	60MPa	80MPa
Expected strain from suction(25kPa)	4.23mm	0.06% =1.9.mm	0.0415% =0.8mm	0.0315% 1.5mm

In total, the settlement might become as about 16mm when the ground water table lowered about 10m shown in Table 6-14.

Table 6-14 Total Settlement anticipated by ground water lowing and suction

Water level	Settlement	Suction	Total
2.5m	4.1mm	1.9mm	6mm
5.0m	8.5mm	2.7mm	11mm
10m	16.7mm	4.23mm	21mm

6.10 Ground behavior and wall inclination

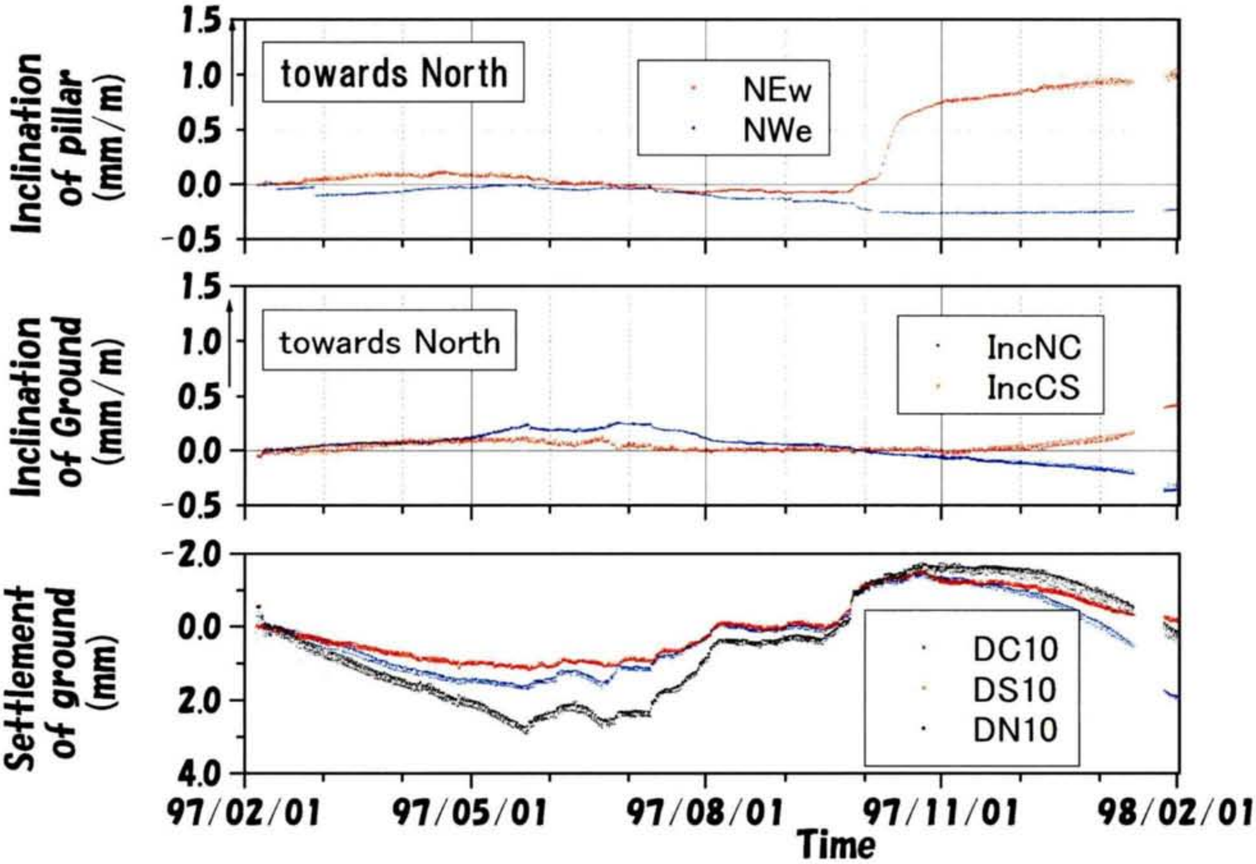


Fig.6.27 Settlements at north, center, and south points, inclination of masonry pillar at NE and NW corners, and inclination of ground

Fig.6.27 shows settlements at north, center, and south points, inclination of masonry pillar at NE and NW corners, and inclination of ground estimated by settlement measurements.
The inclination of the ground is computed as

$\alpha=(\delta N-\delta C)/\Delta$ (mm/m)
$\beta=(\delta C-\delta S)/\Delta$ (mm/m)

where,
δN, δC, and δS: settlement at north, center, and south point in mm.
Δ: distance between north and center, and center and south point.

Before the heavy rainfall in the end of September 1997, a slight tendency of inclination of ground toward north in Fig.6-27 and shows the peak in July and turns toward opposite direction.

The inclination of masonry pillar takes the same tendency until the heavy rain in September. The increases of the inclinations of the pillars are found no relation with ground behavior.

If the tower inclination has been caused by the ground settlement/heaving, the inclination should be the same trends of the ground behavior.

The allowable settlement to keep the masonry structures from differential settlements is not known at this time. It is necessary to keep the present underground condition and to continue to monitor the ground water level as well as responses of the masonry structures to prepare any situations that may occur in the future.

6.11 Cause of long creep behavior - ground or laterite block of the foundation –

The differential ground settlement might have caused the inclination of the N1 tower. However, it was observed that the ground settlements after the heavy rain had shown the much more settlements at north point than those at south, which should have given the northward inclination. This contradicts with the measured inclination. Another possible reason is the deformation of laterite block of the foundation. Since the laterite block of the foundation is severely weathered, we could anticipate that the deformation of laterite block have caused the sudden change of the inclination of the tower from the ground.

If the laterite block of the foundation causes the creeping of the N1 tower, what kind of phenomena shall be expected to occur?

We observe many cracks in the weathered laterite blocks and the soil grains flowing out from the blocks with rainy water. We see that the weathered state of the laterite block is under self-crash/self-restructuring stage. Wet and dry weather effects of heavy rainfall and strong sunshine might have caused the heavier weathering of laterite block of the upper structure. We observe that the laterite blocks of the foundation at Prasat Suor Prat have been weathered which wet and dry effects especially at the changing level of surface water might cause.

We could assume this weathering state of the foundation laterite block and further the laterite block had cracked because of small deformation of the blocks themselves, which may be caused either by ground heave or by strong wind during the heavy rain in September 1997. Once the crack(s) had developed within the laterite blocks, it will give a good reason for the present long term creeping. The laterite block, after being cracked, is difficult to recover its strength have to continue their relative small movements towards the most stable state of deformation.

6.12 Conclusions and Some recipe for repairing principle based upon Prasat Suor Prat N1

In Chapter 6, stability of Prasat Suor Prat was discussed based upon observation of present structure. Among 12 towers of Prasat Suor Prat, S6 Tower was already failed. These Towers are independent squired structure of 10m x 10m in width and about 15m in height. N1 Tower is found at the most critical state against collapse among the rest 11 Towers in terms of the present inclination and N1 Tower was discussed in detail.

The mode of deformation was studied by leveling the stone surface and measurements of dimensions of basic length of the structure. Based upon differential height of the foundation along the peripheral of the Tower, we found the foundation of Tower N1 inclined to northwestwards with 0.4m/10m.

There are four walls, each of which has opening in squired shape of about 2m in length. The horizontal beam element of sandstone at the bottom of opening is found collapsed. The collapse was caused by complex mechanism including bending and shear failure caused by overstressing of foundation laterite block beneath the horizontal beam.

The bottom lengths of the openings are longer than the top one with about 10cm.
The foundation of the structure is made of masonry laterite blocks. The horizontal openings between adjacent blocks are measured. The horizontal spreading was concentrated for Towers nearby Ponds. The Tower load nearby the embankment caused the displacement of the embankment towards pond, which has caused inclination and spreading of the foundations of the Towers. The sum of opening for each wall corresponds well to the difference of top and bottom length of opening in walls. It is concluded that the foundation has been spreading out horizontally that makes wider bottom dimension than upper one. We measured widths of bottom and top of open windows of other Towers The widening of the bottom widths are found concentrated into Towers nearby Ponds that was estimated by the horizontal outwards movement of the embankment to the pond caused by the load of the nearby the Tower itself. The embankment movement that was caused by the Tower has caused the inclination and spreading of the Tower nearby the Pond.
A fresh crack was found on a surface of a laterite block, which may indicate the continuation of the horizontal spreading. The present structure is not stable and the movement of spreading and inclination may be continued in the future.

The monitoring of behavior of Prasat Sour Prat as well as ground movement and suction pressures were performed. The settlement during cry season and swelling in rainy season are confirmed by seasonal changes of underground water and suction pressure.
If the level of underground water is lowered by 10m, the settlement is anticipated as nearly 20mm, which may be critical to masonry structures.

It gave a suggestive result that we did have had a chance to observe the long-term creeping phenomena of inclination of the Tower N1, Prasat Suor Prat after the heavy rain in September 1997.
For the upper structure of the N1 tower, it is obvious that we need some counter measures to prevent or to delay the self-crash down from inside. For the foundation, what are the problem and how the countermeasures should be considered?

The large additional increase (1.3mm/m), which is equivalent to 1/30 of the present absolute inclination (about 40mm/m), has taken place within only a year after heavy rain. As already discussed

in the preceding sections, this long term creep might well be considered from the small deformation of the laterite block of the foundation of N1Tower.
Among various countermeasures, the following methods may be considered as internal treatment to retard the failure.
○Keeping the water level constant through rainy and dry seasons to prevent weathering of laterite block.
To obtain more effective results, the surgical operations are recommended as follows,
○Grouting into ground and/or improvement of laterite blocks or
○Replace the foundation with concrete structure, and/or pile foundations to support the load of the upper structure and put the weathered laterite block as only surface decoration.
To apply any kind or measures, a little surgery treatment might cause displacements and local failure of decayed laterite blocks, which becomes easily to fail.

If mechanical treatment of the grouting is applied, the ground heaving is inevitable and difficult to control. If soil grouting or improvement is ever considered, we recommend chemical treatment that increases the degree of improvement gradually with time and allowing monitoring to confirm the allowable effects to the structures.

6.13 Reference

JSA (1998)"Chapter 6 Geotechnology, Geology, and Environment", "Annual Report on the Technical Survey of Angkor Monuments 1998." pp.325-369, JICE, Tokyo

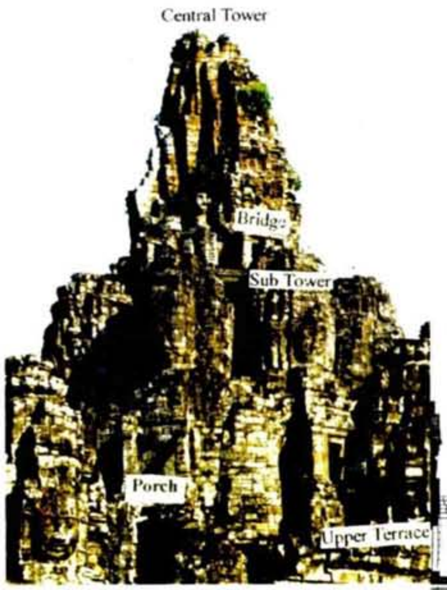
7 Stability of Main Tower at Bayon and some results based upon monitored structural behavior

7.1 Introduction

Japanese Government Team for Safeguarding Angkor (JSA) is preparing a strategic plan how to restore the Bayon temple. Among various structures of the Bayon temple, the main tower is one of the most important and a unique masonry monument. JSA has been working on monitoring the behavior of the tower since October 1997. This paper presents a basic view of the stability problem and failure mechanism of the tower based upon present observation and monitored results.

7.2 Central Tower

The height of the tower is said as 45m and was measured as 42.2m from the ground level at north of Bayon temple by total station by Geotechnical Unit, JSA in December 1998.
The central tower stands upon the upper terrace at GL+10m. The diameter of the tower at the base is about 25meters.
The structure of the main tower consists of central and eight sub towers surrounding the central one with carved face on the outward side. There is a small circular gallery between the central tower and sub-towers, where one may walk around the tower at about mid level of 16m from the upper terrace.



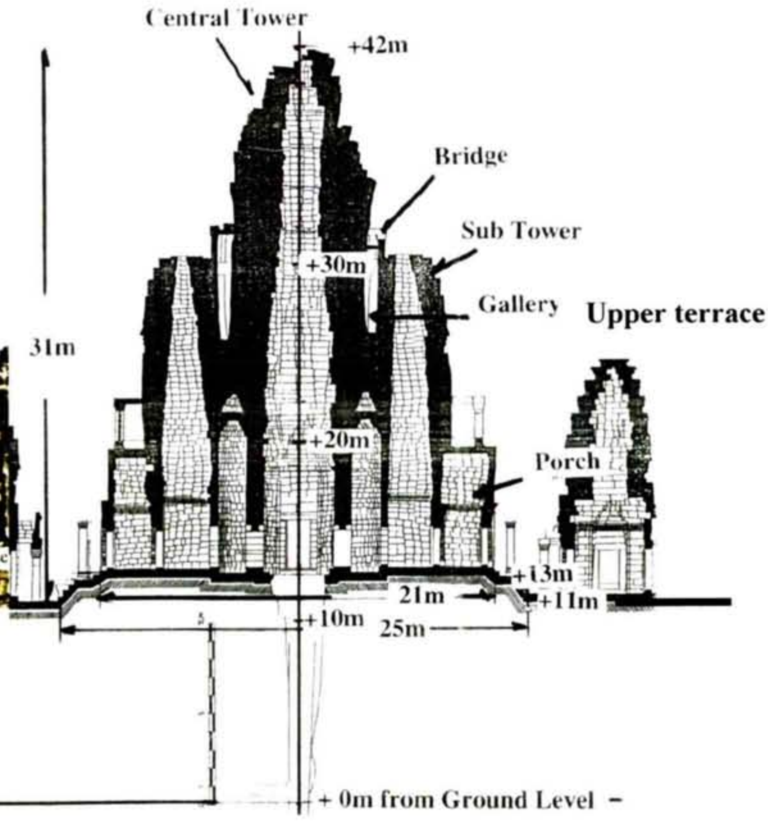


Photo 7-1 The upper Portion of Bayon tower Fig.7-1 Schematic Section of Bayon tower

In February 1998, JSA installed scaffolding ladder in the inner space of sub-tower at southwestern side to go up to the mid level space of the tower from the upper terrace. Using this scaffolding ladder, Geotechnical unit became to be able to install various sensors at the upper level of the tower and to maintain them.

7.3 Structural stability

There are several types of mechanism that may result in some structural failures for the main tower of Bayon. The possible modes of failure of the tower are 1. Overturn failure of total instability and 2. Progressive failure caused by partial instability of the masonry structure.

7.3.1 Total instability of the main tower by large inclination as overturn failure

Inclination of the tower might cause overturning of the tower. Large inclination of the tower results in outward movement of the gravity center of the structure. If the point of the center becomes to locate outside of the base width, the tower structure shall overturn loosing its stability.
In foundation engineering, the allowable range of the center of gravity for design is usually defined as middle third of the base width. One of the famous examples is the leaning tower of the cathedral of Pisa in Tuscany, Italy. The height of tower of Pisa is about 55m with the diameter of 15.6m.

Table 7-1 Comparison of Pisa vs. Bayon in terms of critical angle for overturn failure

	Height	Diameter	Critical ratio (tangent)	Critical angle
Pisa	55m	15.6m	0.09	5.4°
Bayon	30m	21m	0.23	13.0°

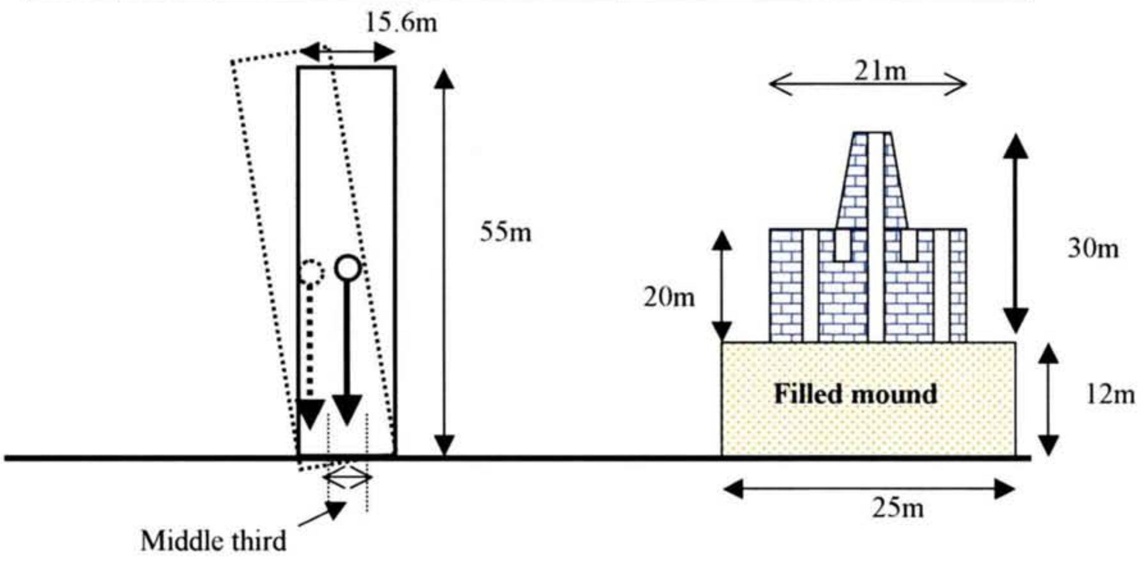


Fig 7-2 Comparison of Leaning tower Pisa and Central tower of Bayon

The total instability problem caused by inclination is sensitive to slender tall structures. If we assume the allowable inclination of the tower as the point of the gravity force within the middle third of the foundation, we can compare the critical angle of both towers as shown in Table-1.

Here, we assumed that both of mass distributions are symmetric and mass centers locate at the middle height of the tower. Since the mass center of Bayon tower is much lower than assumed, the Bayon tower is much safer than Pisa.
As shown later, however, the measured heights of peripheral points along the foundation of the main tower on the terrace floor were found somewhat irregular. The reason of different level is not clarified yet and any effect on the stability to the main tower is another problem to be solved.

7.3.2 Progressive failure of the tower by fall-out of stones and stone failure

In the central tower of Bayon, either dropping out of each stone and stone failure could cause the structural instability as a progressive manner resulting in the total failure of the tower in the future.
As shown later, the apparent side view of the central tower is different depending upon the direction to the Tower, which has been caused by falling out of the stone elements from the central part. We have to study the mechanical process of falling out these stones from the tower body to consider countermeasures to prevent. Since the most stones are simply piled up from bottom to top without over wrapping horizontally, the stone column has been rather easy to lean out if some horizontal movement taken place caused by plant rooting or other mechanisms.
It should be also pointed out that chemical decays were found on the surface of the stones of the towers. These progressive failures caused by mechanical and chemical reasons are considered as one of major factors to be studied for the stability problem.

7.4 Present structural states of the Tower

To understand the present structural states of the tower, we performed leveling of the basement of the main tower of Bayon on the upper terrace, visual observations of outer shapes of the tower, and stone elements, which consist of main tower.

7.4.1 Leveling of the basement of the Central Tower

We have performed measurement of height of the foundation level surrounding the second floor of the main tower of the Bayon, December 17, 1998. Fig. 7-3 shows the plan of the main tower and the measured locations. The results of relative height of the basement of the main tower of Bayon are also shown in digital number in meter. As in the middle of Fig. 7-4, the measured points are numbered and divided into two groups of east and west sides. No.1 point of West Side was selected as a reference point and the height of No.1 (W1) is assumed as 0.0m.
The top and the bottom of Fig.7-5 show the height for northern and southern halves. It is understood that the western side of the tower is symmetrical in height. Both north and south subsided to the centerline. On the other hands, the eastern side of the tower is one sided.

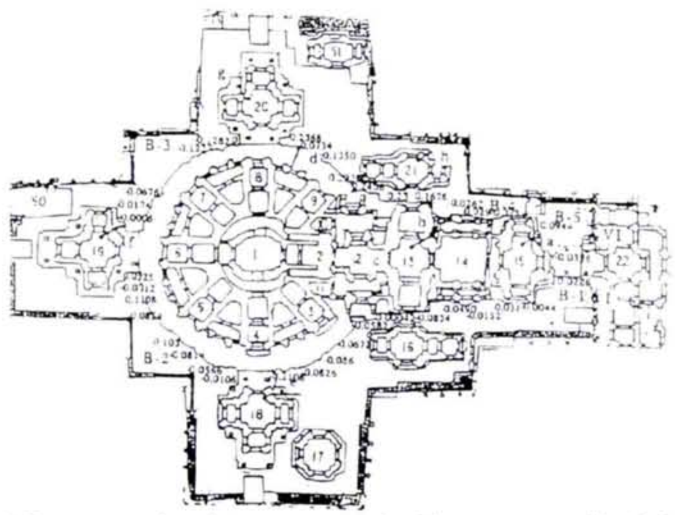


Fig.7-3 Plan view of the Central Tower and points surveyed with measured heights

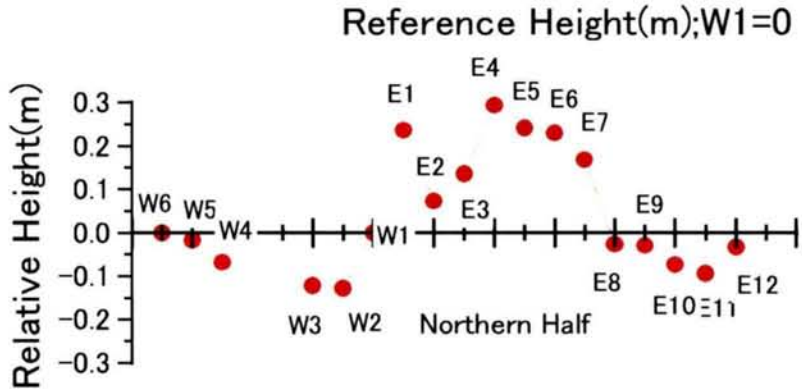


Fig.7-4 Point measured around the foundation of the Central Tower

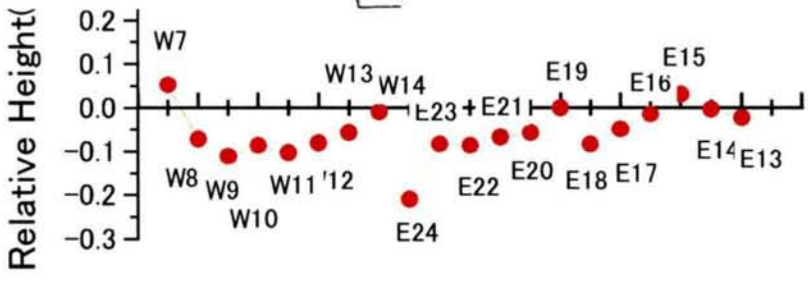


Fig.7-5 Relative Height of Basement around the main tower, Bayon on the Upper Terrace

The northern half (E1to E4) is higher than southern counter part (E24 to E21) by about 0.25m. In the peripheral circle of the central tower, there are some portions of differential height or settlement. However, there in no definite trend to show one sided inclination.

The northern half (from E4 to E7) is also about0.2m higher than the reference level. The southern half (from E21 to E18) is lower than the reference level by about 0.1m. The differential settlement between south and north level is about 0.3m. The reason why this differential height exists is not known.

In some points like W1, W7, W6, and W14, the levels are relatively higher than the neighbor points. These points correspond to the place where some tower structures exist nearby. The points near to such tower structures whose foundation is rather stable might have settled little. Subsidence is recognized at the floor between these structures.

7.4.2 Shape of the Tower

The shapes of the tower from four directions are shown in Photo7-2. Photo7-3 shows one of the four face towers in Bayon temple that keeps its symmetry and is considered as the original shape of the Central Tower.

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Photo7-2 The Central Tower of Bayon from East, West, South, and North directions

Photo7-3 Typical shape of the tower in Bayon

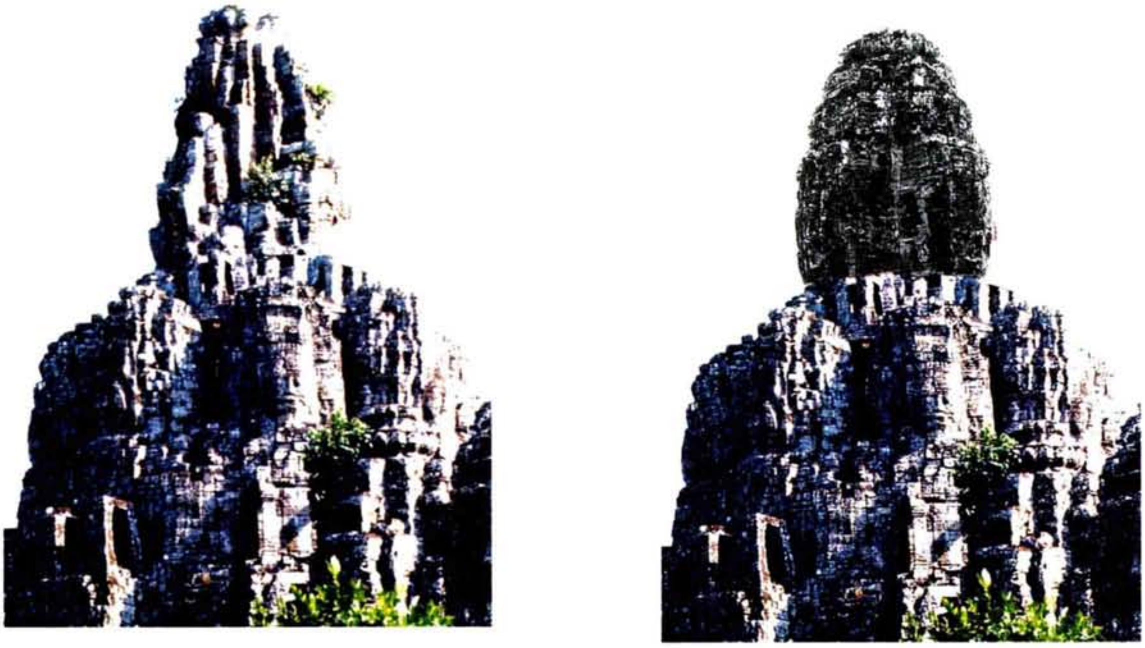


Photo 7-4 The comparison of present and estimated original shape of the Central Tower, Bayon

7.4.3 Bridges between central and sub-towers

As is mentioned previously, the stones are piled up vertically without over-wrapping horizontally each other and most pillars stand independently. Most stone elements bridged between the central tower and eight sub towers are found broken and some are missing. Concrete beams were placed and ion nails were used to retrofit these bridging elements.

These consolidation works were executed by EFEO in 1930.

Openings are found between many neighboring stone columns and most these openings have caused large displacements of the top of the columns that caused damages of bridge elements.

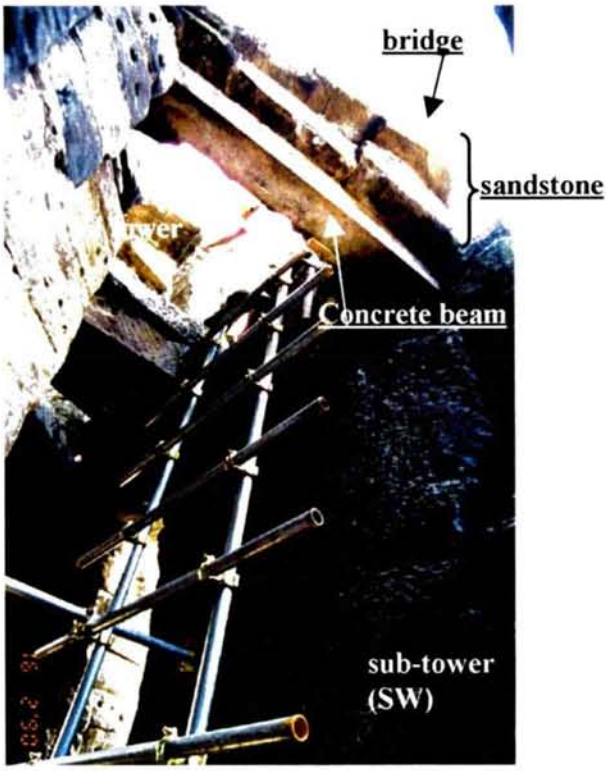


Photo7-5 bridge between Central and sub Towers.

7.4.4 Fall out of stone elements

It is found the lack of the symmetry against the center of the tower. Photo 7-4 shows a comparison of the present and estimated original shape of the Tower. One of the reasons why the outer shape of the tower silhouette differs each other depending on the direction is not known. However, these characteristics of the shape of the tower strongly suggests stone elements might have been fallen out in the long period after being lost by the Khmer Empire.

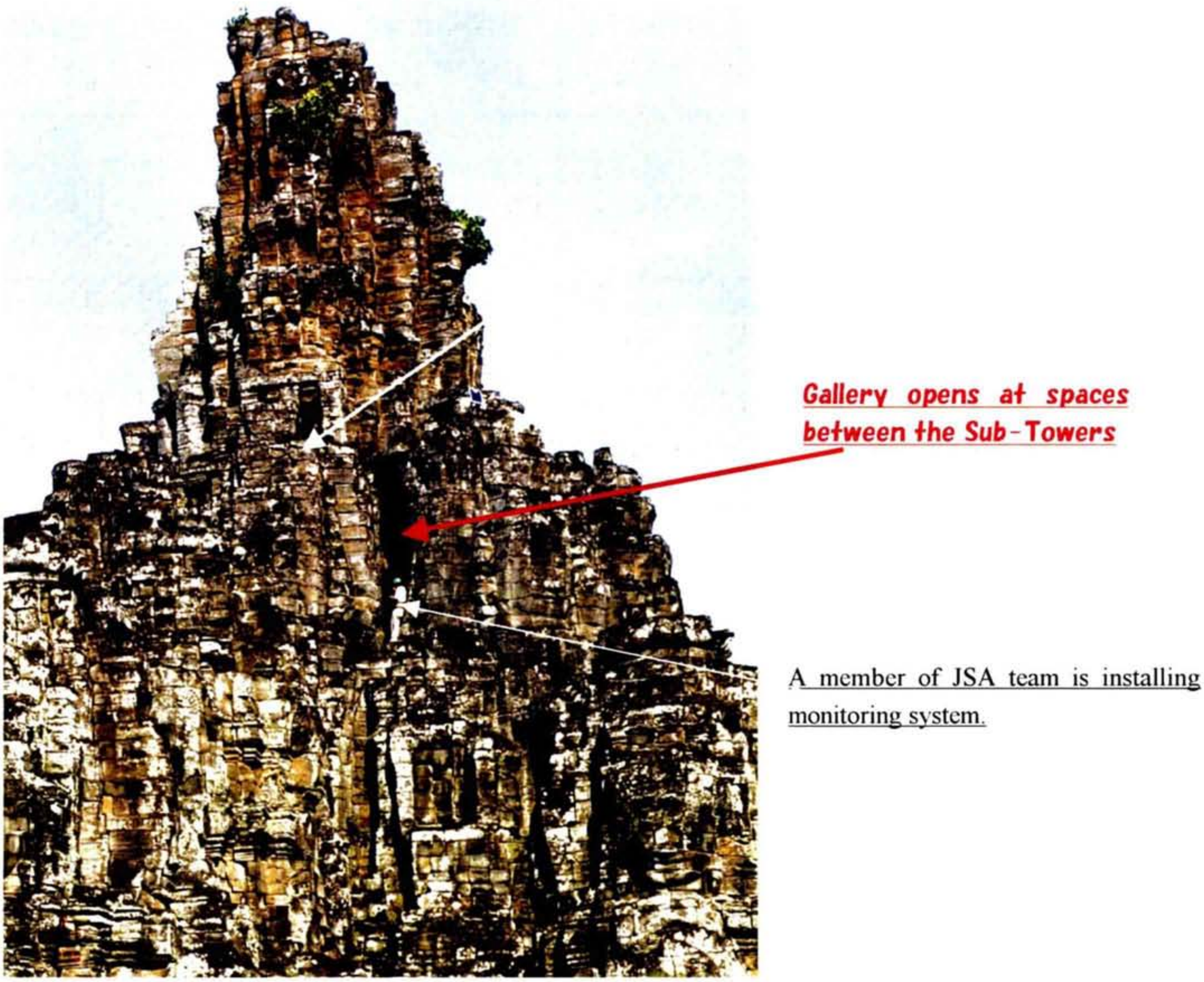
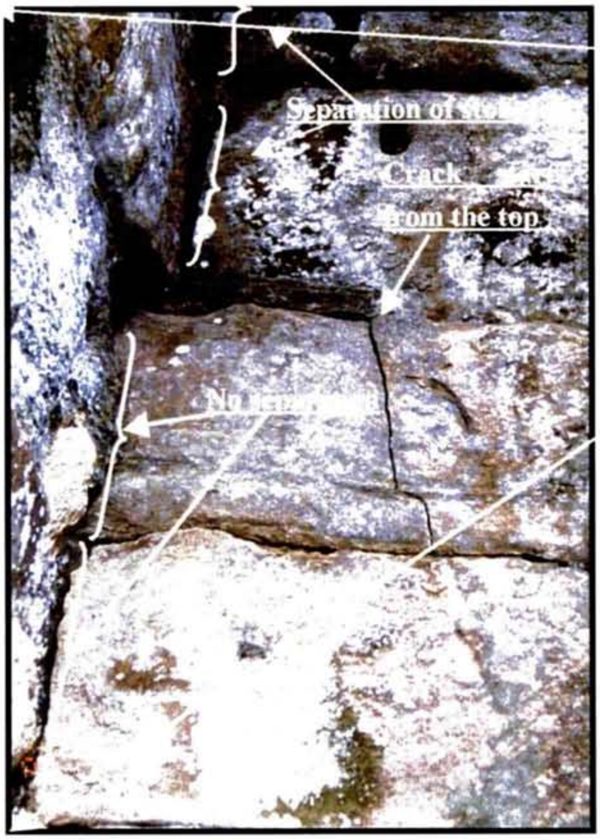


Photo7-6 Gallery of the Central Tower

7.4.5 Lean-out of the stone columns and openings of the adjacent columns



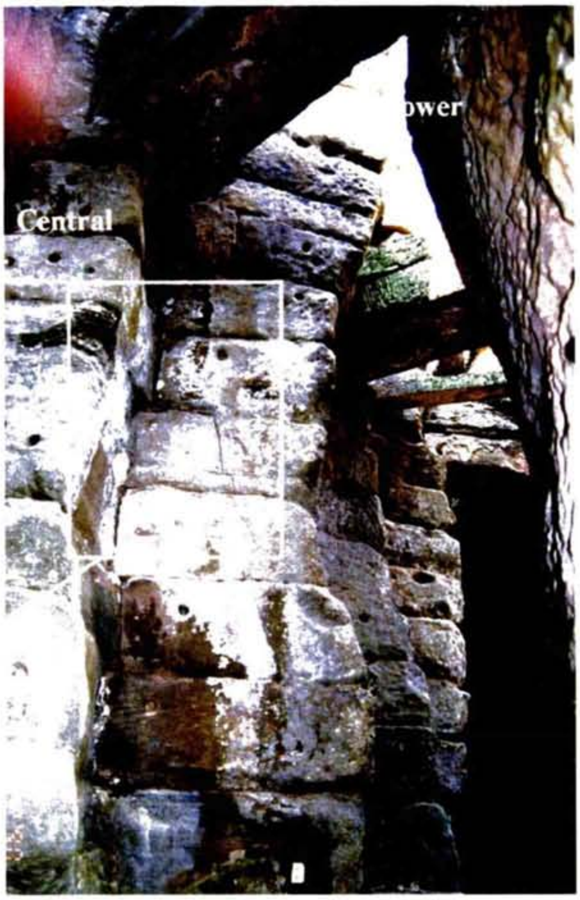


Photo 7-7 Inside of the Gallery of Central Tower (northwest corner)

There is a gallery within the central tower as shown in Fig.7-1, which surrounds the tower at a level of about +25m from the ground level. We can observe the present situation of the fall out process of the main tower. The Gallery is the space between the inner central tower and eight sub-towers. The Gallery is open at the spaces between the sub-towers as shown in Photo 7-6.

Photo 7-6 shows the inside of stonewalls of the Central Tower around the corner of northwest. It should be noted that a vertical crack develops in the side surface of a sand stone at the middle height, which is enlarged and shown in the left of the Photo 7-7. The crack on the stone surface initiates at the upper surface and has developed downwards It should be also noticed that the separation of sandstone above the cracked one from the left neighbor stone, while no separation of the spacing between the cracked stone and the adjacent one. The separation of the spacing above the cracked stone is found continued upwards. At the same time, no separation is found at the lower stones than the cracked one.

There is another example at the southwest corner of the Gallery that is shown in Photo 7-8 and 7-9. Two cracks are shown in the Photos and these cracks at the lower level in the blocks continue upwards with increasing opening width.

Photo 7-9 Enlarged bottom part

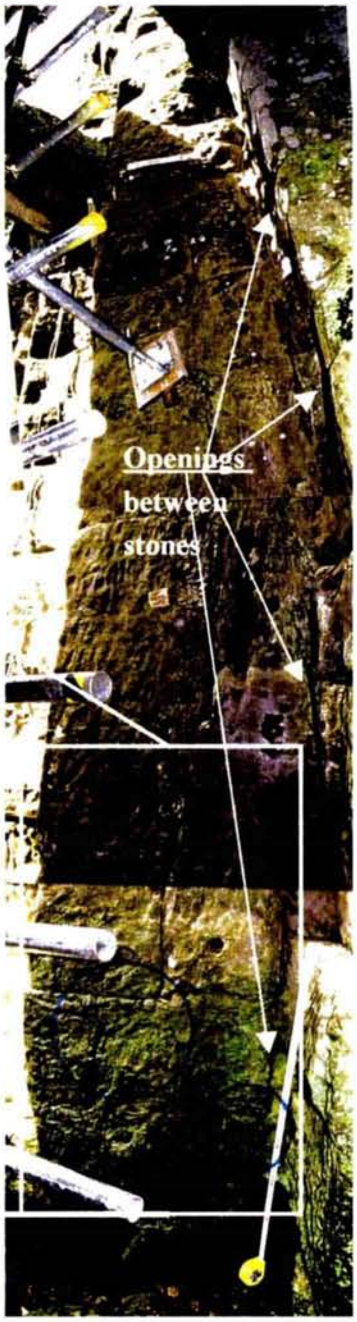


Photo 7-8 Southwest corner of the Gallerv of the Central Tower

We found separation of these stone columns from adjacent ones and most of the opening between columns had been filled with mortar by French works possibly in 1930. The opening ranges from 2 to 5cm in most cases.

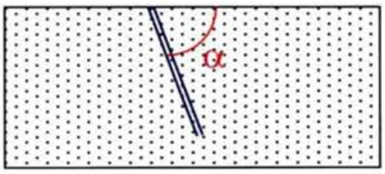
7.4.6 Cracks on the stone surfaces

Several cracks are found on the surfaces of the column stones of the central tower in the circular gallery. The most of these cracks are found at the bottom level of the column stones. A few are found at the mid level. The crack line starts from upper inside on the horizontal surface and reaches at lower outward positions. These directions of the cracks are found in the same for different positions.

It is also found that there is opening of the vertical space between adjoining column. The gap increases with its height, which suggests that the column is inclined outwards from the vertical position.
We measured angles of cracks from horizontal line. Several examples are shown in Table 7-2. The angles are found rather large as large as 70 degrees.
The tendency of large angle suggests that the crack is caused by tension failure due to horizontal force given by forced outwards displacement.

Table7-2 examples of angle of crack from the horizon

number	α:Inclination (in degree)	Wall position
1	70	SW corner
2	45	SW corner
3	70	NW corner
4	70	EN corner
5	70	NW corner
6	60	NW corner



Plant root
Photo 7-10 Plant root between vertical gap (SE corner)

The forced displacement might be caused by horizontal widening of the spaces between columns at upper level by some reasons under the condition of being fixed at the bottom level stone to the floor stone. It is expected that an increasing friction force had been mobilized between the stone surfaces at the bottom due to the horizontal movement of the column. Photo 7-10 shows plant root grown in the gap of stones. It is obvious the plant root develops with enlarging the size of the root that makes widening the space between stones.

Photo 7-10 shows another example of space widening phenomenon. Several gravels are found in a space between stones. It is not known how these gravels had fallen and stayed, however, these gravels might have acted as non-reversible ratchet. Once the opening of the space increases by some reason, gravels fall down and keep the space wider than before.

Photo 7-11 Gravels fallen in space opening between stones

7.4.7 Stress conditions to cause the tension stress by horizontal movement

If the friction force had exceeded the maximum available frictional resistance, the upper stone might have slid over the surface. The maximum frictional resistance is the product of vertical load multiplied by frictional angle between the stone surfaces.

When the shear force is applied to the horizontal stone surface with vertical load, the stress condition in the lower stone causes compression and tension force as follows,

Vertical stress on the surface $P_v = \rho h$

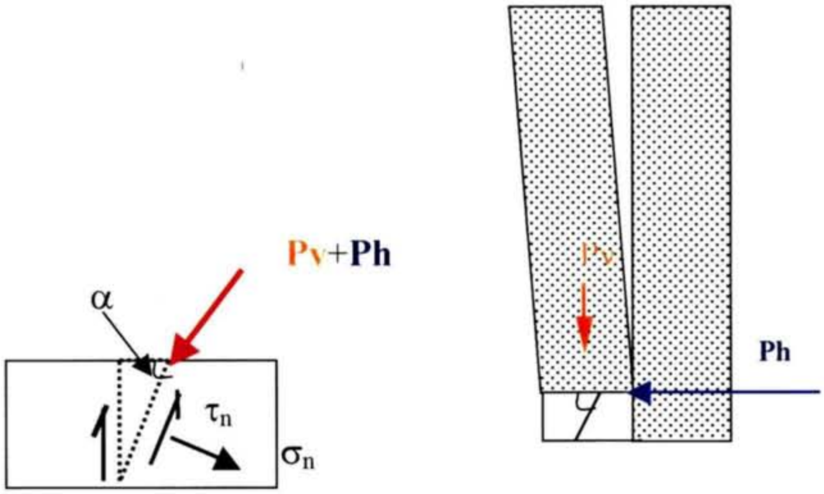
Frictional stress on the surface $P_h = P_v \tan\phi$

where

ρ: density of stone (MN/m^3), h: height of stone column above the stone

ϕ:Angle of friction between stone surfaces

The forces on the surface cause change of stress condition within the stone material. We consider stresses on a plane perpendicular to the horizontal surface. Let the angle of inclination of the plane from the horizontal surface be α as shown in Fig.7-6.



inclined angle: α

Fig.7-6 Stress state under lean out

The normal stress on the plane with inclination α is

$$\sigma_n = \boldsymbol{Pv}\sin\alpha - 2\boldsymbol{Ph}\tan\alpha\ \sin^2\alpha$$

The tangential stress on the plane is also expressed by

$$\tau_n = \boldsymbol{Ph} - \boldsymbol{Pv}\cos\alpha\sin\alpha - 2\boldsymbol{Ph}\sin^2\alpha$$

If no horizontal force is applied, the normal stress becomes always compression and the crack is identified as caused by compression shear. When the horizontal force is applied at the upper surface of the stone, the normal stress becomes tension on plane with some range of inclination angle about $\alpha \sim$ $60\text{-}90^0$.

The range of the angle where the tension stress appears depends upon the intensity of horizontal stress. The possible types of failure of stones which causes cracks is either compression shear or tension failure. No further discussion is made here in terms of stress condition due to lack of the information of rock strength. However, the possible mechanism found in this case is rather tension stress than compression shear.

7-5 Monitoring of the structural behavior

In 1997, we have installed several gap gages to monitor the changes of gap between the surfaces of the adjacent stones at the central tower of Bayon. We thought it might be a good idea to develop an initial image on the mechanism of the decay and possible structural modes of movements.

Access to the Central Tower of Bayon and height level to install inclinometer

If we install any sensors at upper portion of the central tower, we need some measures to reach the sensor points for maintenance work. When we installed gap sensors at the middle level of the tower in 1997, we used temporary pipe framed scaffolding at northeastern side of the tower to gain access the upper level of the tower. Since the scaffolding is temporary use, we need more stable measure for long-term use and we have constructed a ladder inside the sub-tower at south side of the main tower.
If the main tower is divided into three leveled structures of top, middle, and bottom parts, we can easily reach at the middle level of the tower by the inside ladder. For the top-level part, however, it is still difficult to reach and to work safely.
If we assume some sets of inclinometers to install at any one of these three parts, we may compare theses three cases as in Table 5-1 for various points of view. We evaluated that the best performance may be obtained to install inclinometers at the middle level.

Table 7-3 Comparison of location for installing sensors

	installing level of the main tower		
factors to be compared	**bottom part**	**middle part**	**top part**
differential settlement of foundation	detectable	detectable	detectable
deformation from lower part	detectable	detectable	detectable
deformation from upper part	not detectable	detectable	detectable
easiness of install and maintenance	easy	possible	possible/not easy long maintenance
evaluation	+	++best	+

7.5.1 Monitoring system

We began to monitor behavior of stone by installing gap sensors between adjoining stone faces in October 1997 and inclinometers at central tower in February 1999. Since then, though missing data for some period, we have continued monitoring.

At the middle level of the central tower, there are eight sub-towers surrounding the central one. We have installed six micro crack gages between vertical opening of adjoining stones of side walls of these sub-towers. One inclinometer on four faces of N, E, S, and W each and two inclinometers on four corners of NE, ES, SW, and WN each have been installed to monitor the inclination of the central tower.

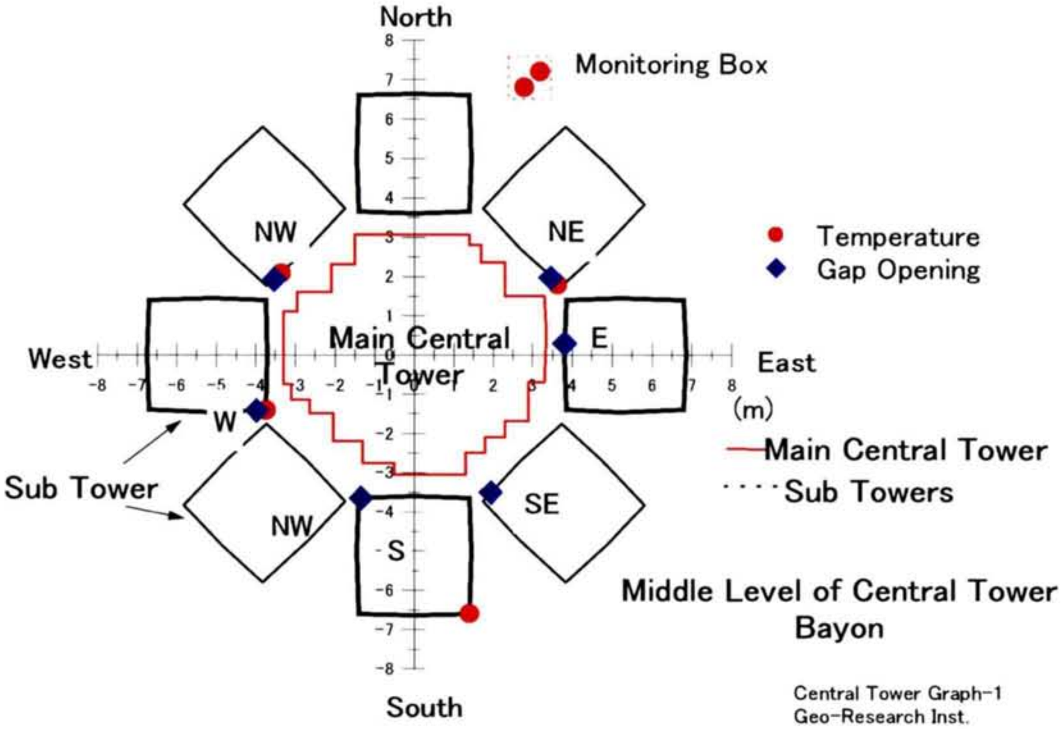


Fig. 7-7 Plan view at the mid level of main tower with Location of Sensors

Fig.10-7 shows plan view of the middle base level of the tower with location of sensors of temperature and gap. The analog signals from these sensors are transmitted down to the monitoring box at the base level of the central tower and are to be digitized with a sampling rate of an hour and stored in a hard memory. Solar Battery has been used to drive the whole system with back up lead battery being charged during day.

A local staff has retrieved these data every two or three weeks.

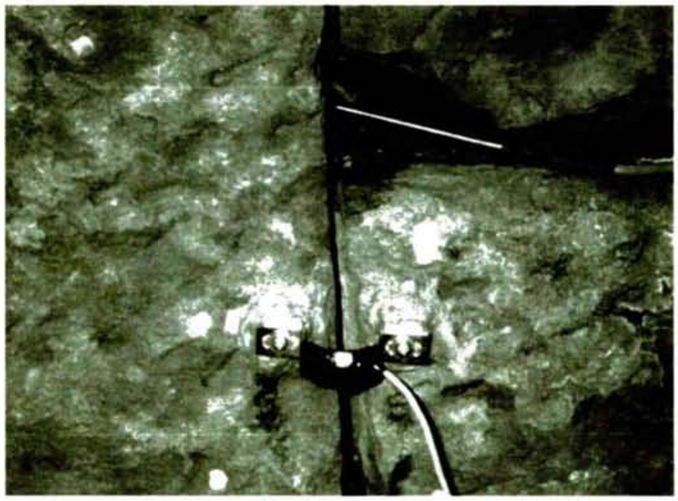


Photo7-12 Gap opening and temperature

Photo 7-13 inclinometer installed on the Core Wall of Central Tower

7.6 Daily and seasonal change of gap opening

Photo7-12 shows an example of installation of a gap sensor and thermometer at NW sub-tower. The measured data of changes of gap and temperature from October 1997 to November 1998 are shown in Figs.7-8 and 7-9. The sensors are named as NE, NW, W, S, SE, and E according to the directions of sub-towers that are being monitored. Figs.7-10 and 7-11 also show the same data only for three-month period from May 1, 1998, where the more detailed movement can be observed. Among six sensors, it is noticed that the trend of gap changes has some common and different characteristics. The daily change in common is found to close the opening the gap in daytime and to widen in night. The magnitude of the gap closing and widening is different for each point. The temperature changes shown in Fig.7-10 also have different characteristics for each point. Temperature sensors at NE, NW, and W are located at the gap sensors except at S sub tower point where the sensor is exposed directly to the sunshine.

Table 7-4 Gap Opening daily and annual change

Gap point	NE	NW	W	S	SE	E
Daily gap change (mm)	0.02	0.05	0.03	0.01	0.01	0.01
Daily temperature change (°C)	5	5	10	(30)		
Annual gap change(mm)	0.5	0.5	0.2-0.5	0.1	0.1	0.1

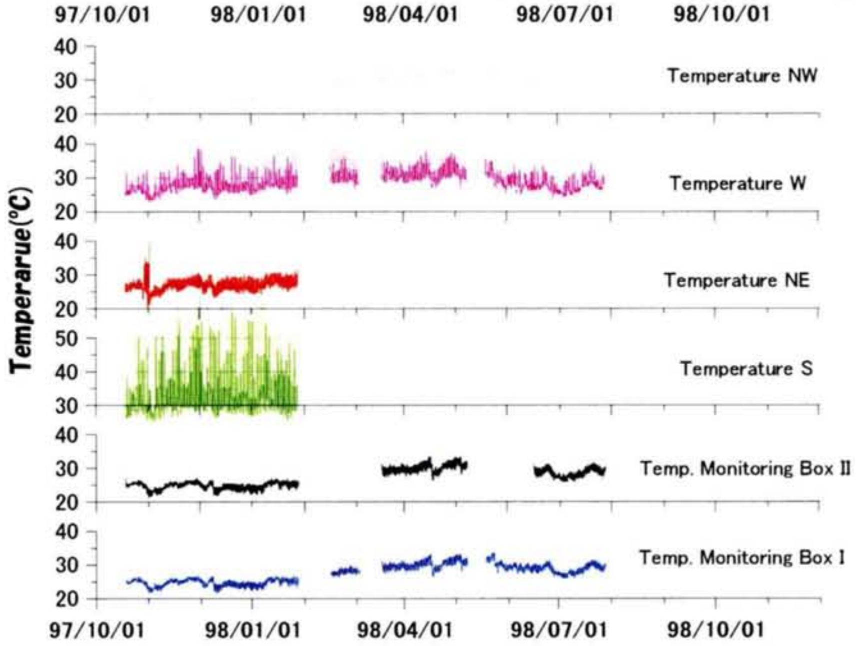


Fig.7-8 Change of Temperature at Central Tower

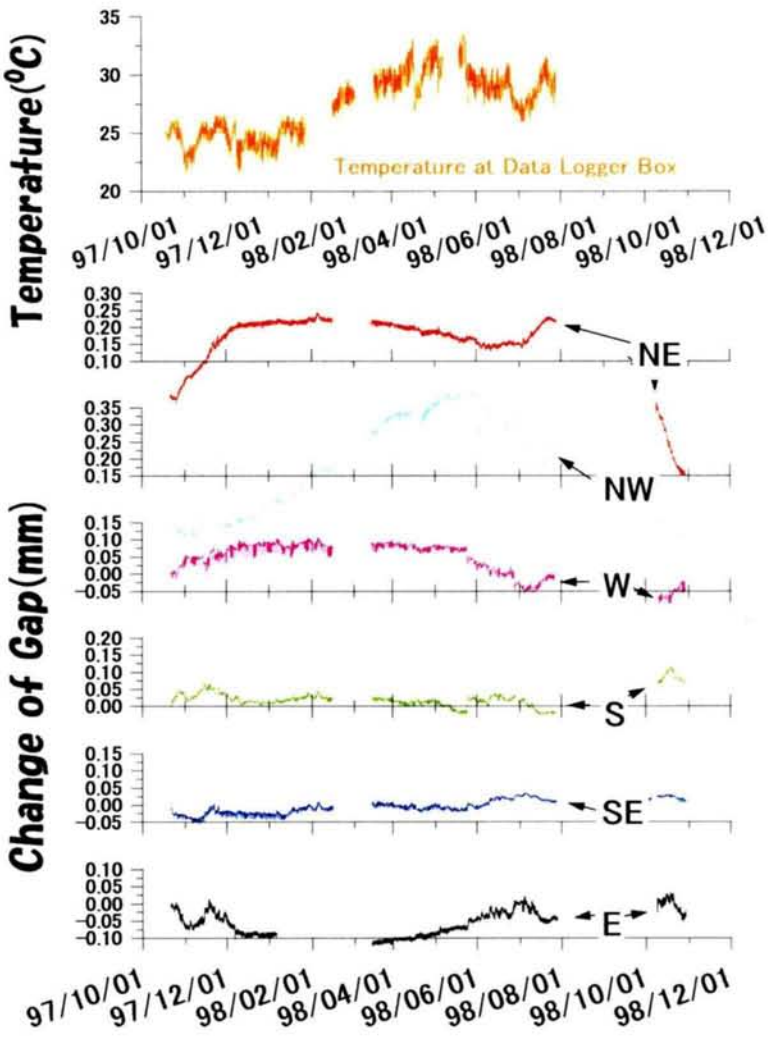


Fig.7-9 Change of Gap of Opening at Central Tower Bayon

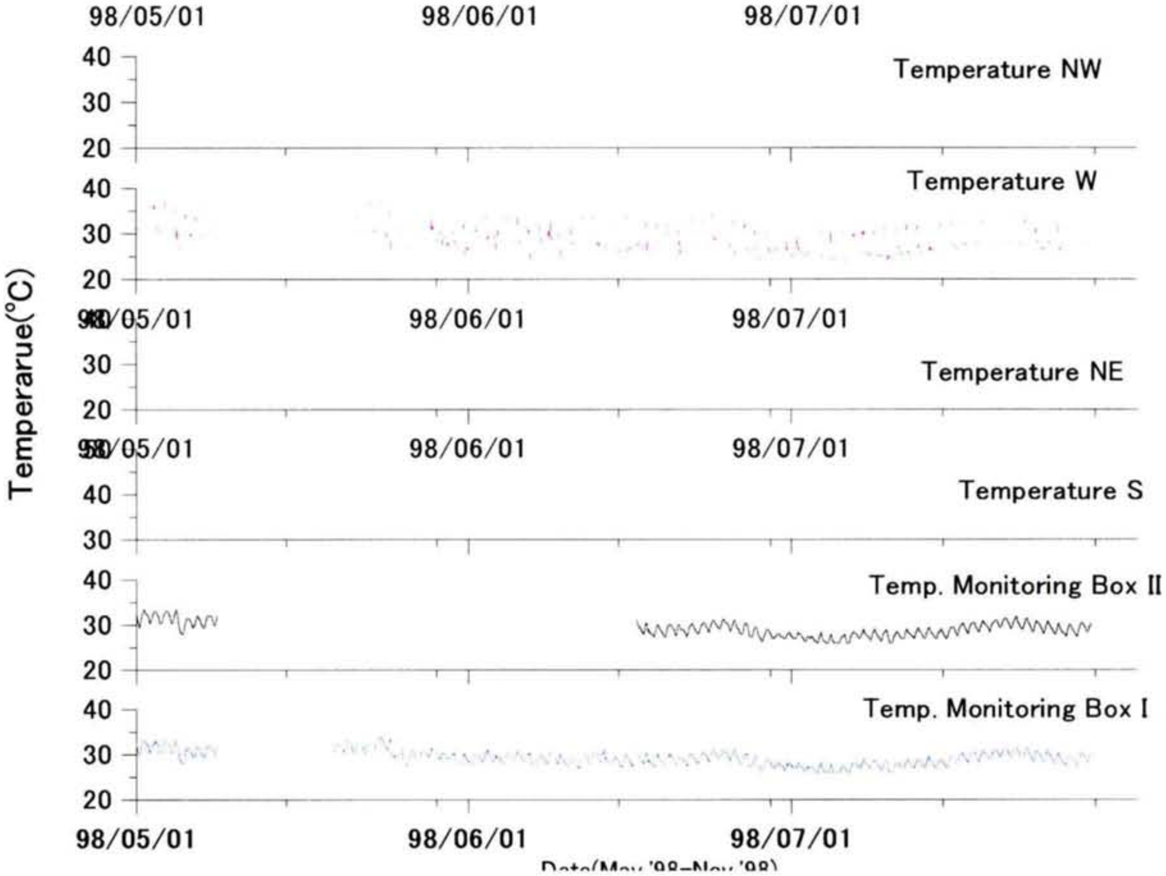


Fig.7-10 Change of Temperature in three months (May 1 to Aug 1, 1998)

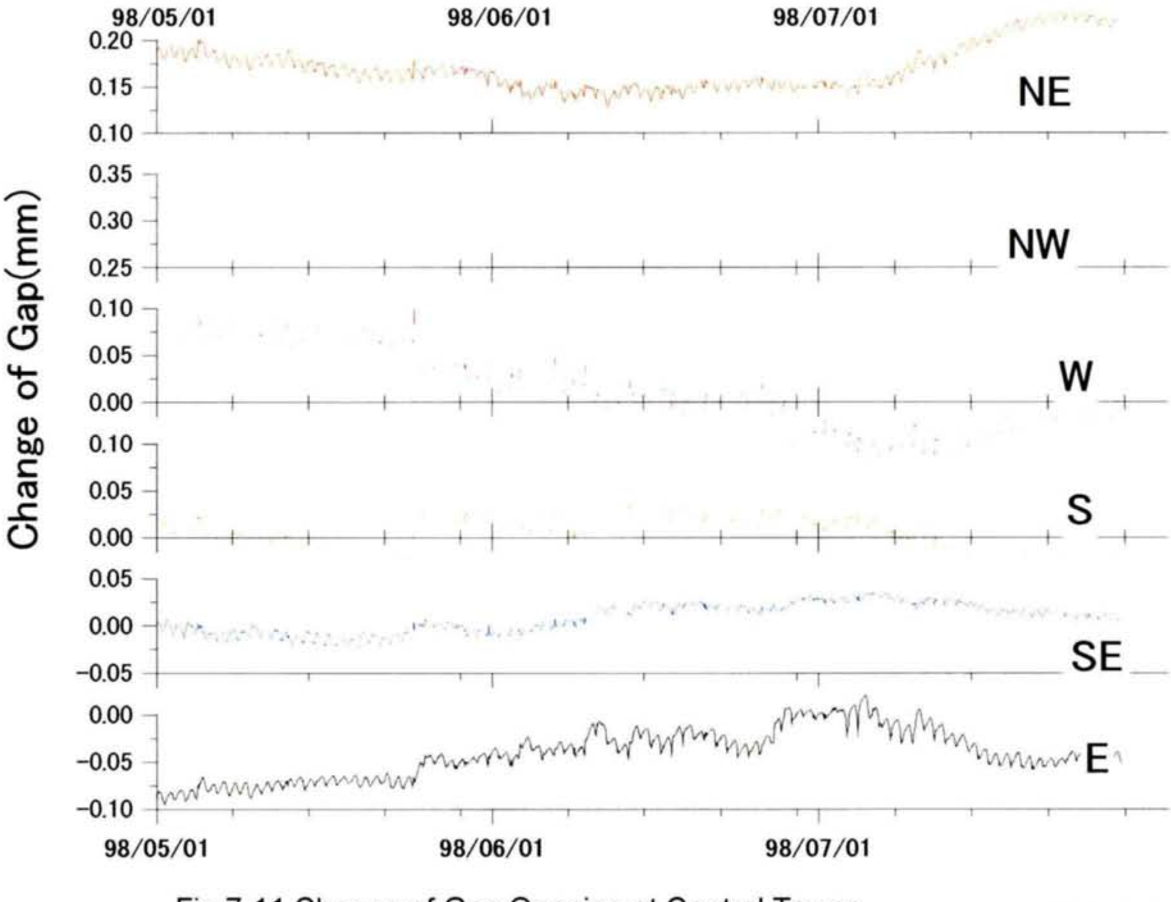


Fig.7-11 Change of Gap Opening at Central Tower

WindRain Grap-6
Geo-Research Inst.,Osaka

Two other sensors were installed within the monitoring boxes of II and I, which contain A/D converter and storing instrument. These boxes are placed within one of the open space in the north side of the sub-tower surrounding the central tower. The temperature within the box is expected less affected by outer field condition. Table 7-4 lists the magnitude of typical daily change of gap opening and temperature, and annual change of gap opening. Among six sensors, S, SE, and E points are a group of small daily change of opening gap of about 0.01mm.

The largest change is found at NW point with 0.05mm. Since the temperature sensor is not embedded within the stone surface but only placed at the surface, the sensor is monitoring basically air temperature being affected by wind blows. S point is more affected by direct sunshine by absorbing sun energy.

The relationship between the magnitude of gap opening and temperature is expected. It is found in Fig.7-9 and 7-10 that the gap opening becomes wide when the temperature change is also large for each sensor.

However, the comparison of gap opening and temperature changes among different points does not show the quantitative relationship between gap opening and temperature change. It is expected that how much the gap closes or opens depends not only the temperature change but also some mechanical characteristics related with the specific site condition. The seasonal change of gap shows their extremes at different times according each point. Though it is difficult to reduce any conclusions on the seasonal changes, it may be found that some relationship between the gap and temperature in a period from June 1, 1998 to August 1,1998 when the both record show some trends. During these two months, the temperature decreased, reached its minimum, and then increased. The most of the gaps except NW point show the same characteristics with different trends. For these points of S, SE, and E, gap opening increased, reached their maximum, and decreased. For other points of NE and W, the opening decreased, reached their minimum, and then increased. NW point is difficult to be grouped into which group it belongs. The gap movement of NE point is unique and different from any other points. It increases from October and reaches its maximum at the end of May, decreases, and reaches its minimum.

7.7 Temperature effect on strain of the stone surface and gap opening

To understand the temperature effects on the gap change more clearly, we have embedded temperature sensor within stone at 2cm from the surface at SW gap point in September 1999.

Fig.7-12 shows the relationship between strain of the stone surface, temperature inside the stone, and the gap opening of space between adjacent stone.

It is clearly found that the gap decreases with temperature increase when the strain increases. The response of the gap well corresponds to the strain of the stone surface.

Fig.7-13 shows strain vs. temperature changes. The relationship between strain and temperature is found as

$$\Delta\varepsilon\ (\mu) = 4\Delta t\ (^{\circ}C)$$

The coefficient of temperature expansion (α) of the sand stone is obtained as

$$\alpha = 4 \times 10^{-6}$$

The average length of the stone is about 50-80cm. The expected gap for 15°C of difference in temperature is expected as

$\delta = 15 \times 4 \times 10^{-6} \times (0.5\text{-}0.8)(m)$

$\delta = 30\text{-}50\mu m = 0.03\text{-}0.05mm$

The measured gap change is 0.025mm, which well corresponds to the estimated value.

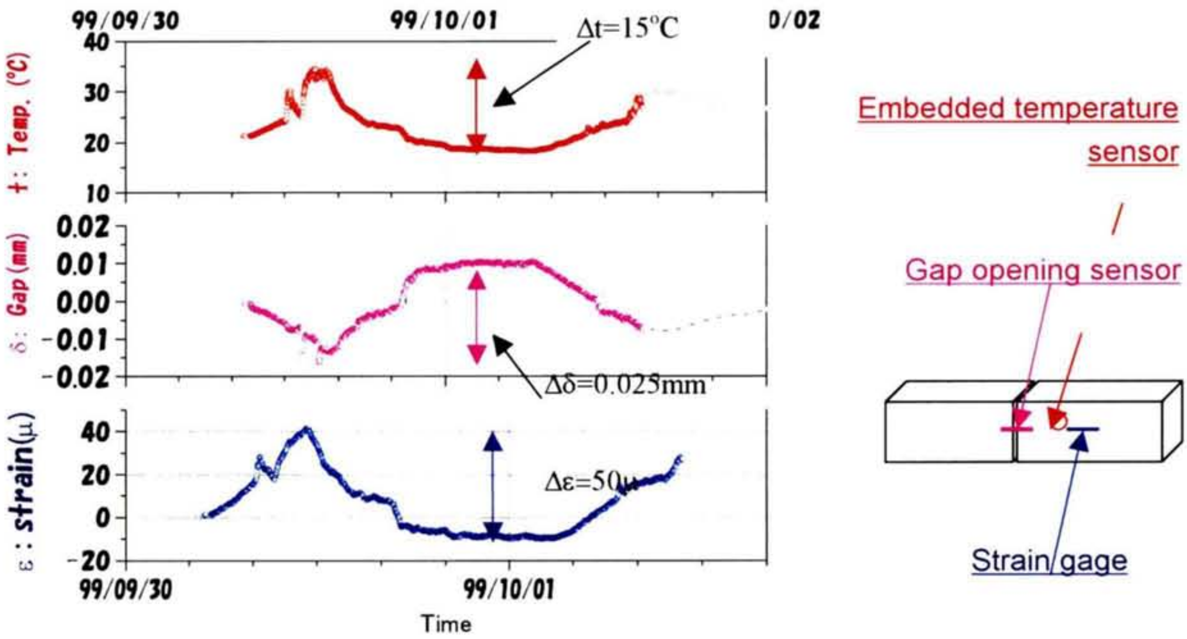


Fig.7-12 Temperature, strain of stone surface, and Gap opening

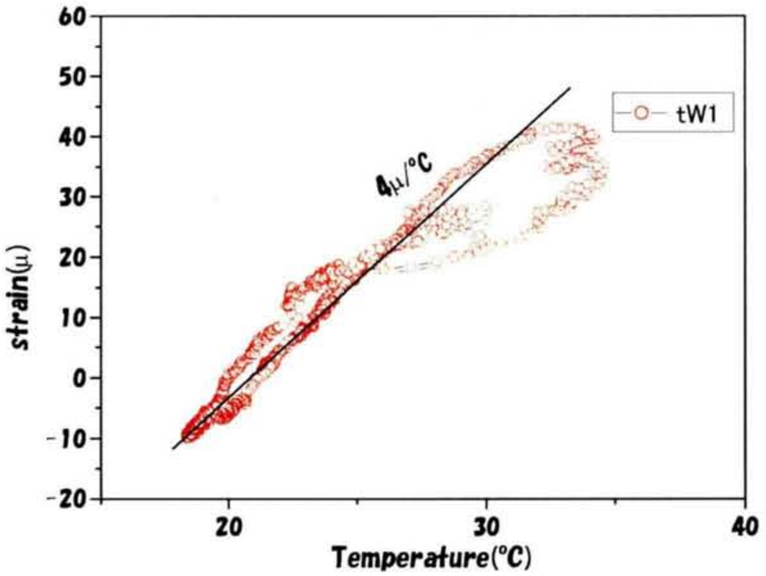


Fig.7-13 Change of strain of stone surface and temperature

It was shown that the basic behavior of change of the gap between stones is the elongation or shrinkage of stones caused by temperature change.

However, the comparison of gap opening and temperature changes among different points in Fig.7-9 and Fig.7-10 does not show quantitative relationship between gap opening and temperature change. It is expected that how much the gap closes or opens depends not only the temperature change but also some other characteristics related with the specific site condition. The seasonal change of gap shows their extremes at different times according each point. Though it is difficult to reduce any conclusions on the seasonal changes, it may be found that some relationship between the gap and temperature in a period from June 1, 1998 to August 1,1998 when the both record show some trends. During these two months, the temperature decreased, reached its minimum, and then increased. The most of the gaps except NW point show the same characteristics with different trends. For these points of S, SE, and E, gap opening increased, reached their maximum, and decreased. For other points of NE and W, the opening decreased, reached their minimum, and then increased. NW point is difficult to be grouped into which group it belongs. The gap movement of NE point is unique and different from any other points. It increases from October and reaches its maximum at the end of May, decreases, and reaches its minimum. The mechanism of these different characteristics to temperature change is not understood.

7.8 Sudden change of gap opening

Among the continuous change of the gap opening, it is also found some sudden change as found on May 23,1998 in Fig.7-11. On the day, the temperature decreased in sudden. The gap opening of NW, W, S, SE, and E had increased except NE point. Within a few days later those of NW and W points decreased, but those of S, SE, and E continued as sudden increased opening.
To see any relationship with other meteorological data, hourly rainfall and hourly maximum wind velocity monitored at the south library of Bayon are shown in Fig.7-14 and 10-15. These sudden changes are found concentrated rather in the rainy season from mid April as shown in Fig.7-9. Comparison between Fig.7-11 of gap opening and Fig.7-15 of hourly rainfall and wind velocity for three months after May 1998, it may be expected that the value of the hourly maximum wind velocity is more likely to be related than rainfall.
Based upon the gap records, hourly gap changes are computed and shown in the upper part of Fig.7-16 with hourly maximum velocities. The relation between the hourly gap changes at NW point vs. the hourly wind velocities in the same time range shown in the lower part can be understood that the stronger wind velocity had triggered the larger sudden gap change in the same hour duration. We may define a critical wind velocity over whose value large sudden gap changes are observed. The critical wind velocity at NW point is about 4km/sec.

The relation of sudden gap(δ:μm) is expressed as a function of the wind velocity(v:m/sec) as follows,
$\delta=2(v-4)$

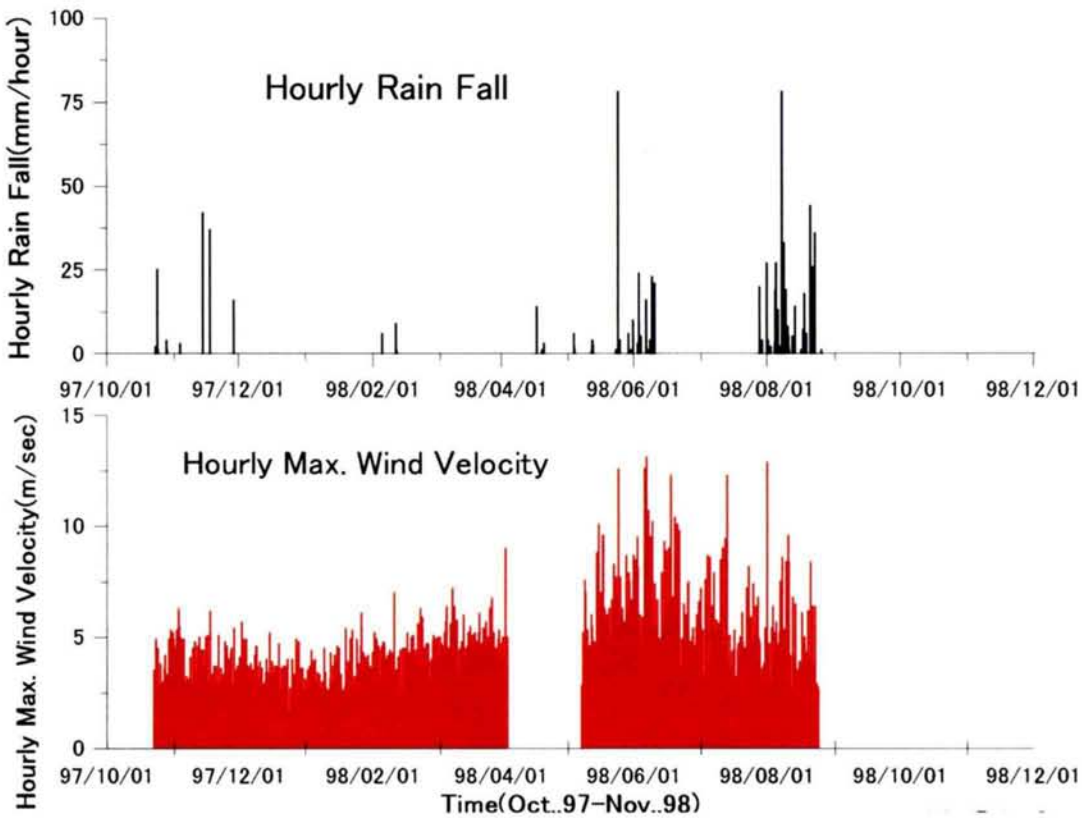


Fig.7-14 Hourly rainfall and maximum wild velocity at Bayon from 97/10/01 to 98/12/01

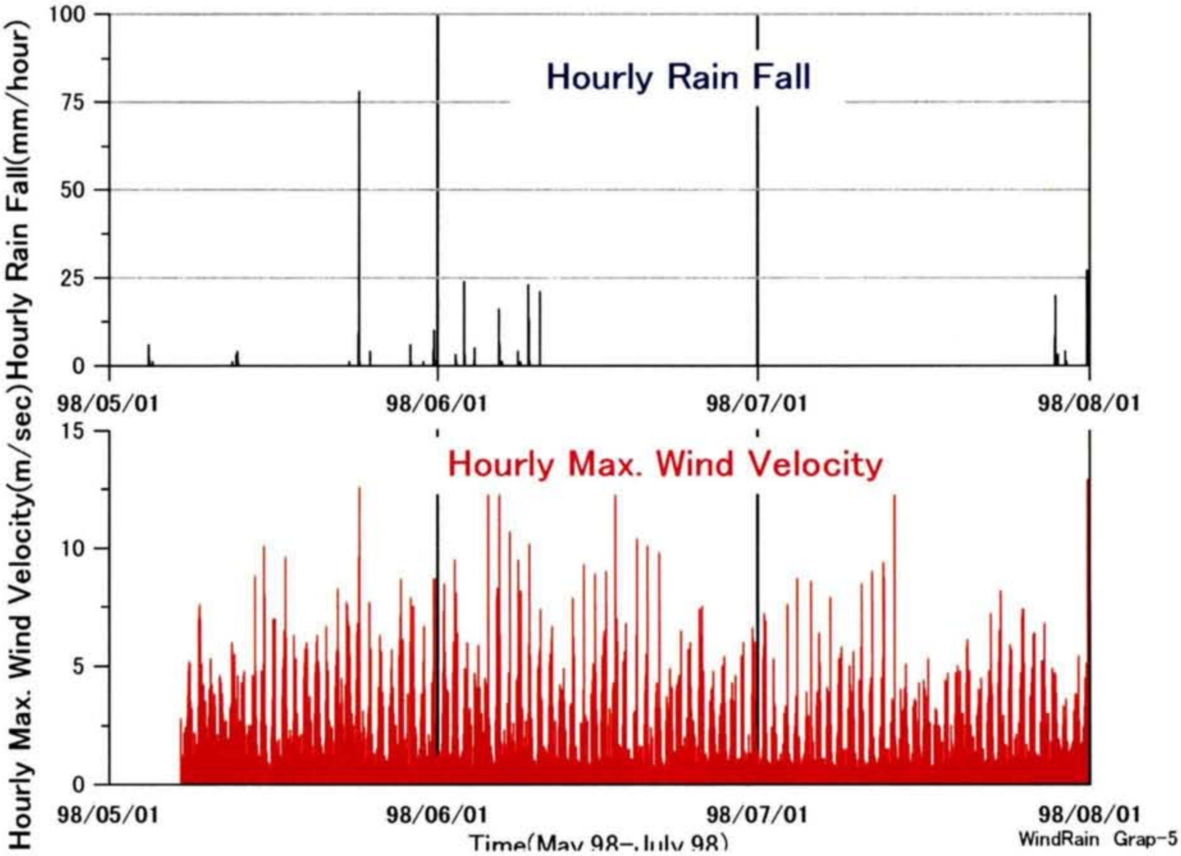


Fig.7-15 Hourly rainfall and maximum wild velocity at Bayon from 98/5/01 to 98/8/01

As already noted, since the gap change is basically temperature dependent and the sudden change inevitably includes those caused by the temperature. The average amount of the daily change of increase/decrease at NW point caused by temperature is about 0.025mm. The averaged rate of the

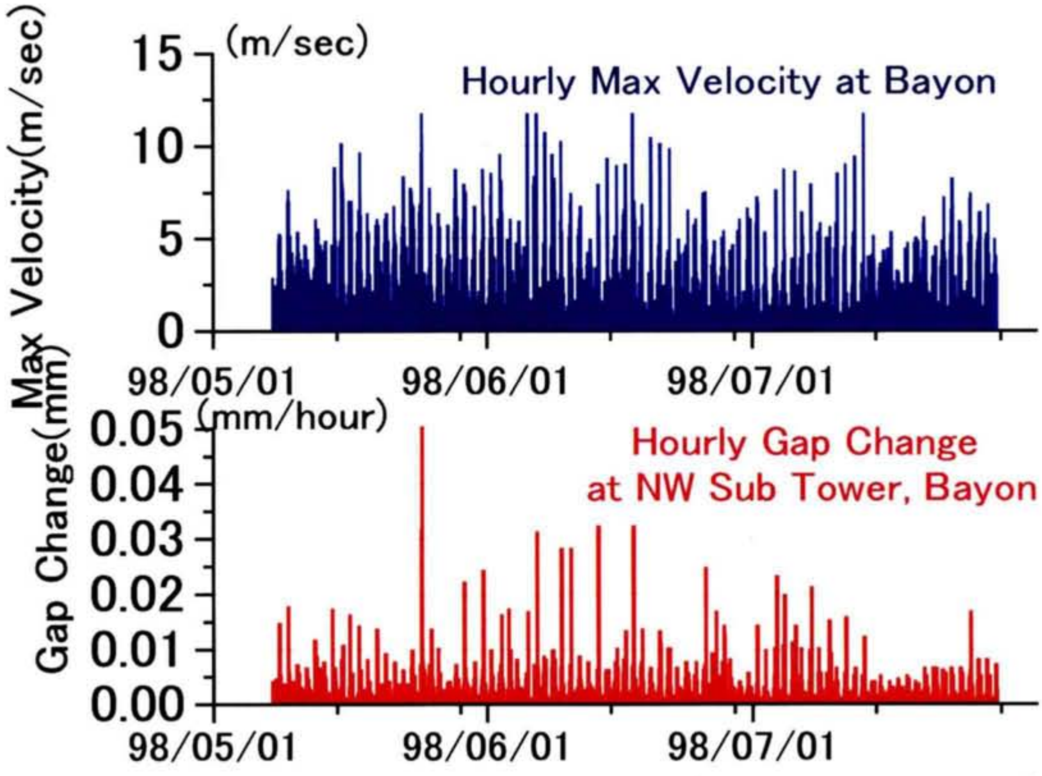


Fig.7-15
Hourly rainfall and maximum wind velocity at Bayon from 98/5/1to8/1

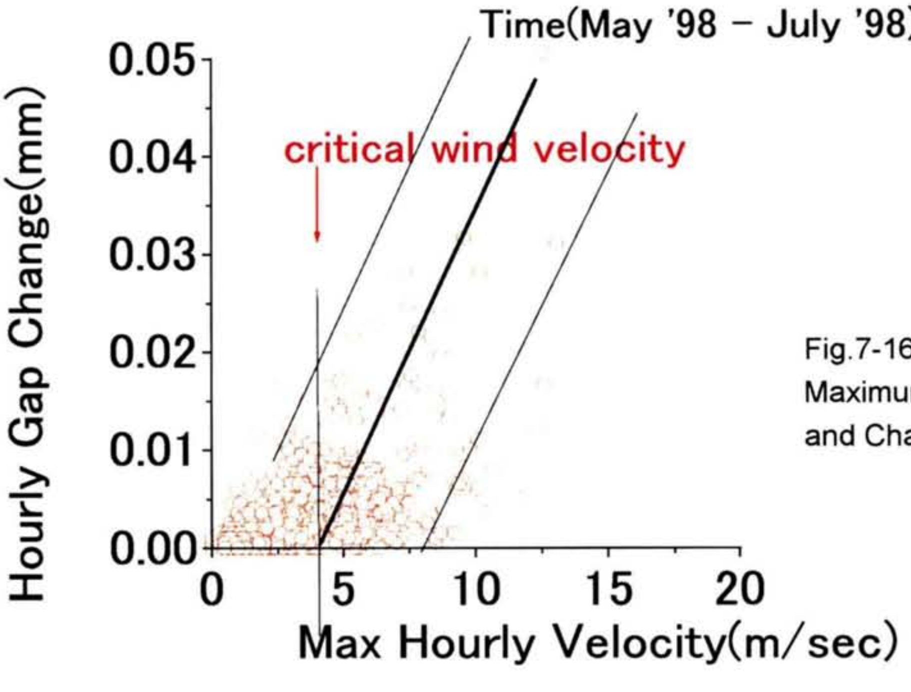


Fig.7-16
Maximum wind Velocity and Change of NW Gap

Max Wind Velocity vs. Change of NW Gap Monitoring Point

change is 0.025mm/6hours, which may correspond about 0.04mm of the critical wind velocity

Table 7-5 Characteristics of sudden change of gap opening

Gap point	NE	NW	W	S	SE	E
Response to wind velocity	Very small	Large	Medium	Medium	Small	Medium
Rebound ability	?	Yes	?	None	None	None/?

As mentioned above, gap opening responds with strong wind velocity instantly. However, the sudden gap change does not always accumulate in the following period. For example, the gap change at NW point suddenly increased at the strong wind always takes the opposite direction and has returned to the original gap opening after 2-3 days. On the other hand, these sudden changes at W points stay as shifted values. The rebound response to return to the original position may be due to mechanical stability of the stone tower. Strong wind causes a small displacement between stone elements, which is basically a result of response of the tower structure against wind. In 1994, the micro-tremor of several structures in Angkor area were measured (JSA report, 1995) and revealed the existence of the natural period for masonry structures and the related mode of movement. The micro-tremor of the main central tower should also be monitored to relate the gap displacement with the structure itself as well as wind force

It is well observed that the horizontal sliding between dry masonry stones takes place easily if a few small particles of sand grain are inserted within the stone surfaces. Botanical root grown between the gaps of the stone boundaries also causes horizontal displacement resulting in fall out. The mechanical behavior of non-reversible character of stone masonry depends upon displacement and the resistant force and relative movements among selected masonry elements may reveal the basic mode of reversible and non-reversible movements.

The above-mentioned analysis of response mode of tower against wind is not only useful for estimation of stability of the tower itself but also useful to select countermeasures against fallout of the stone element from the tower

7.9 Conclusion

Stability of the Central Tower of Bayon is quite different from what is considered for Pisa tower in Italy because of the aspect ratio. It is apparent to see the lack of the symmetry of the Tower. The major reason of the non-symmetry of the Tower is estimated to have been caused by falling out of the outer surface stones one by one in progressive manner.

Based upon visual observation, we found the several facts that might be related with instability of main tower.

1. Fall off of stone element from central tower.
2. Different height of the base level of the tower foundation on the upper terrace
3. Damage of Bridge between central and sub-towers.
4. Vertical opening of the stone columns of central tower

5. Cracks on the stone surface that may be tension failure caused by horizontal movement and/or lean out of the stone columns.
6. Rooting between the stones has caused vertical opening of stone columns. Small size sand and gravel tumbled in the gap between the stones also have caused to widen the opening.
7. Heavy chemical weathering on the surface on the stone were identified.

The process of falling off the outer stone is estimated as follows.

1. Lean-out of the masonry column by some reason
2. Horizontal displacement of the pillar initiates tension failure in the bottom stone beneath the pillar.
3. Progress of tension cracks finally causes failure of the bottom stone.
4. The bottom fails, which may results in whole column above the stone fall-out from the Tower.

Monitoring of open/close of gap between stone blocks revealed that the strong wind has resulted in non-reversal type movement, which may cause lean-out horizontal displacement of the masonry column.

Based upon monitoring of gap sensors and inclinometers, we observed some behavior of the tower and obtained conclusions as follows.

1. Gap between stones opens at night and closes in daytime, due to the change of the temperature.
2. Sudden large gap changes have been observed when the strong wind blows with greater than 5m/sec. The wind action may induce to accelerate the vertical opening between the stone columns.
3. Change of inclination of central tower was observed within a few mm/m in the last ten months. Since the monitoring has interrupted for some duration, the observation is to be continued.

Further necessary works are as follows.

Geotechnical condition under main tower of Bayon is to be studied.

The reason for the different height of the foundation level of the main tower at upper terrace is to be examined.

Since the fall-out of stones from the central tower is one of major process of structural failure, some possible countermeasures should be considered and compared theoretically and through experimentally.

Displacement between the central and sub-tower is to be observed to evaluate the structural stability and to consider countermeasures to consolidate bridge beam portion of the tower.

The weathering process of the stones of the tower and evaluation of the decaying is necessary to prevent or postpone the weakening the stones.

7.10 Reference

JSA (1999)"Annual Report on the Technical Survey of Angkor Monument 1999", JICE, Tokyo, 199-245

8 Restoration Work of North Library at Bayon Temple, Angkor Thom

8.1 Bayon Temple

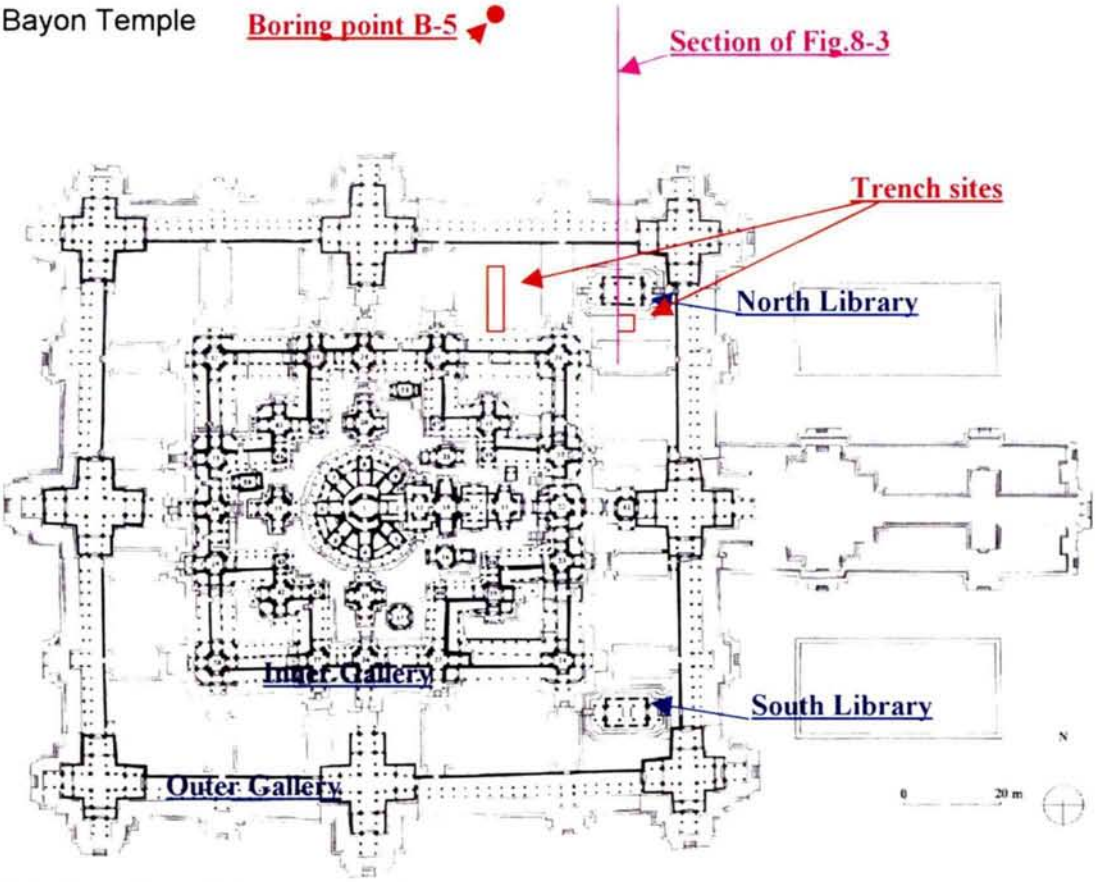


Fig.8-1 Plan-view of Bayon Temple

Photo 8-1 Arial view of Bayon from south-west

Fig.8-1 shows plan view of Bayon Temple in the center of Angkor Thom. There are two libraries in front of east side within outer gallery.

.As shown in Fig.8-1, Angkor Thom ("*Thom*" means big in Khmer) locates north south of Angkor Wat enclosed by rectangular wall with 3km of each wall length. Bayon temple was placed at the center of the Angkor Thom and was constructed based on Buddhism by King Jaya Varmann VII (1181-1220 in position).

King Jaya Varman VII wanted to make of his kingdom a "mandala" where the gods would be pleased to reside. As seen in every monument in Angkor, the Angkor Thom was surrounded by moat symbolizing Ocean and the Holy Mountain "*Meru*" in the center, where gods stays.

Bayon originates "*Beyaka*" from *Sanskrit* or "*Palanka*" from *Pali* language and means "royal throne" or "altar."

In the center of the Bayon, the central tower of about 45m in height are surrounded by 54 towers of four faces, inner gallery, and outer gallery.

When you enter from east front gate, which puts four faces, you will find many towers with four faces stand around with higher level as you approach to the central *Mt.Meru*(Photo.8-2).

Photo 8-2 The Way to "*Mt.Meru*", Central Tower from inside of outer Gallery East side

Inside of Outer Gallery, you walked upon the stone paved terrace and you will find two independent structures at both corners of southeast and east-north. They are South and North Library of Bayon that are shown in Photos 8-3, 8-4, 8-5, 8-6, 8-7, and 8-8.

8.2 Library

The libraries are masonry structures of about 10m in height, about 11m in front width, and about 18m in side width. The roofs of both Libraries have been fallen and missing. The structure consists of upper portion of masonry wall with roof and lower portion of foundation of retaining wall.

The walls of upper structure are heavily inclined towards inside (Fig.8-5). The boundaries of porches and the main structures at both ends are found settled and have become the lowest level. Lintels of porches have been strutted against structural collapse.

These independent masonry structures, which are named as "Library", however, it is practically impossible to store any books inside due to its open characters against sever climate.

Photo 8-3 South Library, Bayon, Side look from north

Photo8-5 Inclined wall and column of upper structure

Photo 8-4 South Library, Bayon, front view from west

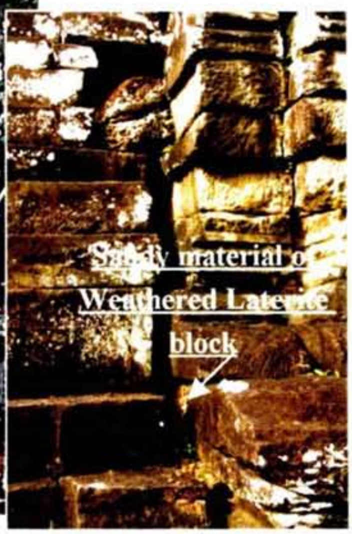


Photo.8-6 South-west corner of the foundation

Ends of both sides are found to have deformed extensively outwards. Careful inspections of the basement of the platform have revealed that there is little uneven settlement at the bottom line of the foundation.

At the west and south corner of the South Library, we could see the outcome of sandy materials from weathered lateritic blocks from a large opening between blocks.

Photo 8-7 North Library, Bayon, side view from south

Photo 8-8 North Library, Bayon, front view from west

In Fig.8-7 and 8-8, several large vertical openings are found at the corner of North Library as well South Library.

Most stone elements covering the corner surface of the foundation are found slid outwards. These movements are caused not by the settlement of soil-foundation but by some deformations of the retaining foundation and/or movement of stones themselves.

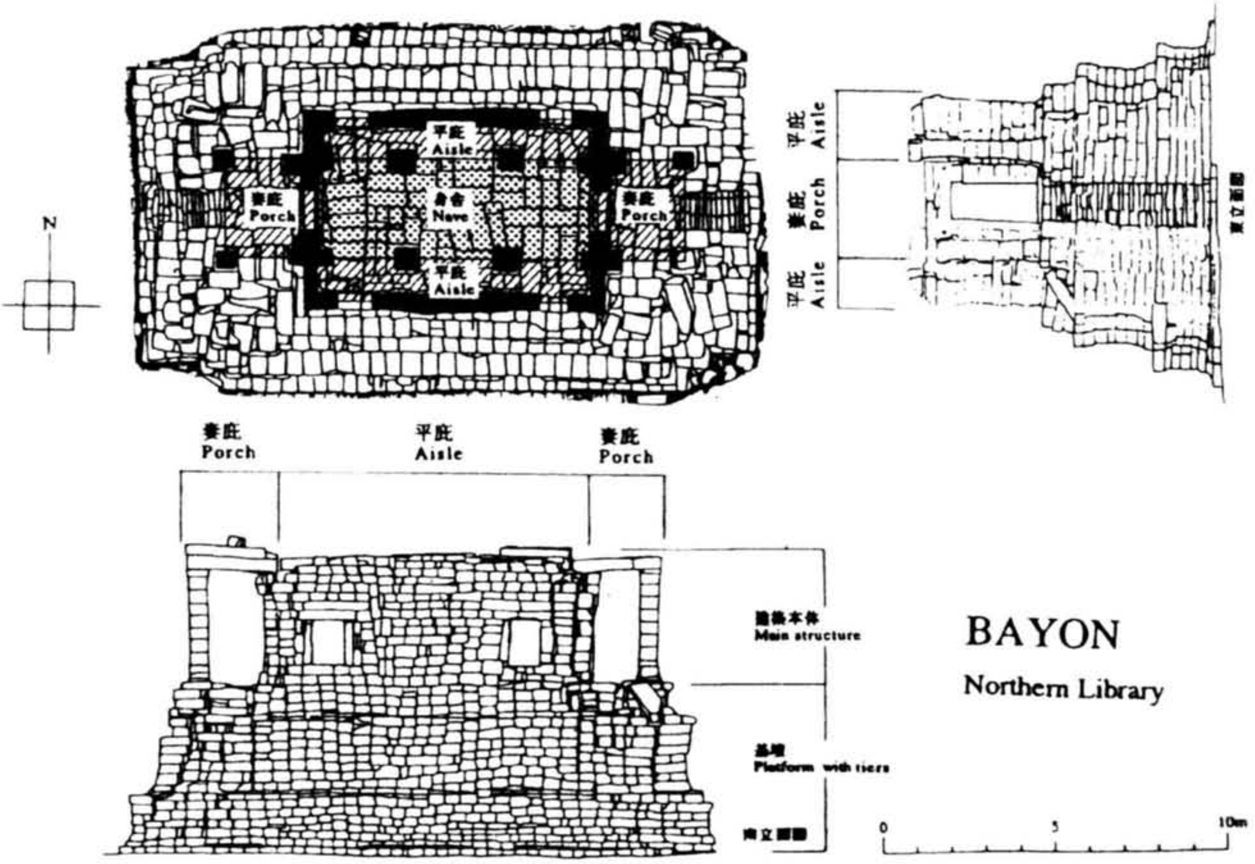


Fig.8-2 Masonry structure of North Library, Bayon

Fig.8-2 shows plan and side views of North Library, Bayon with names of each parts of the structures. The original shape is expected to have an additional roof structure, which has been fallen and missing at present as referred before.

8.3 Geotechnical condition at Bayon Temple

Fig.8-3 shows vertical geotechnical section from north to south near the North Library, Bayon temple (see Fig8-1 for section line). In the left, the boring log is shown as well as the results of DCP (dynamic cone penetrometer) and SPT (standard penetration test). Clayey silt layers are in dark yellow in color. Two sand layers are identified as upper layer from GL-6 to GL-9m and lower layer from GL-11m. As discussed earlier, two sensors of pore water pressure were installed and show different characteristics. Rainfall is also shown to compare the water level changes. It should be realized that there are two kinds of response to rainfall. One is very quick response of water pressure to the rain in the upper sand layer. Another is rather seasonal characteristic, which shows the highest water level is at the end of rainy season.

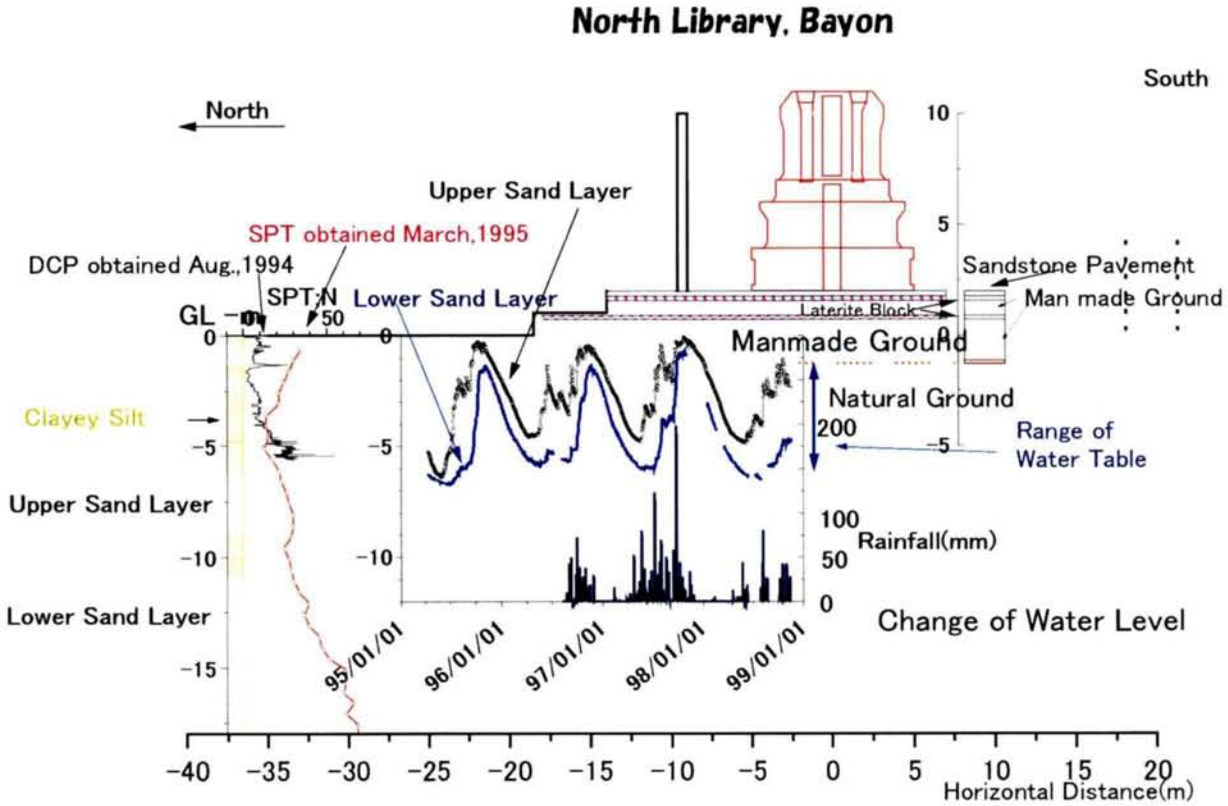


Fig.8-3 Vertical N-S section near North Library, Bayon Temple

The lowest water levels within a year are found in the beginning of rainy season. As discussed in the preceding section, the soil strength becomes affected in the upper 4-5m caused by seasonal changes of water level. The strong effects are wetting and drying of the top surface ground during these seasons. The soil becomes very stiff in dry season and shows very high strength. On the other hand the soil becomes soft in rainy season and shows rather weak in strength. The top 4-5m from the surface was found heavily affected by the seasonal effects.

The foundation of soils in Bayon is well-compacted sandy layer. The geological and geotechnical conditions have been studied by sampling of soil at trench excavations by archaeological unit, JSA. The site was selected at the same trench excavated by the EFEO some 50 years ago. Beneath the top pavement of sand stone, laterite block layer was found followed by man made fill of 0.6m in thickness was found in eight sand sub-layers. Another laterite block layer of 20cm in thickness was laid below this soil layer. Beneath this lower laterite block, compacted fill of 13 sandy layers of 160cm in thickness were identified down to level of −1.15m.

These manmade soils are well compacted with the alternation of sand and clayey sand layers. We performed a cone penetrometer test at the manmade soil. Cone resistance was found about q_c=2MPa(20kg/cm^2), which may correspond SPT N-value of about 10-20. The soils backfilled by EFEO was also tested and found to have a rather low value of q_c=0.5MPa(5kg/cm^2). This weak character of backfill in the old trench may imply that they did not care controlling of dense compaction process when they refilled the excavated trench. The soil should be compacted well enough when any trench is to be refilled. The long-term effects of loosening of the soils underneath pavements might cause infiltration of seepage into underground structures of Bayon.

Recently, the archeological trench was excavated just north of the Inner Gallery. It was found that below the surface sandstone, laterite blocks, and lower laterite blocks, well-compacted fill was extended about 6m from the surface of sandstone pavement.

Based upon these facts, the ancient Khmer engineers made the following ground treatment before constructing masonry structures.

1. Excavation about GL-4m.
2. Compacted fill to GL+0.5m
3. Lower laterite blocks
4. Compacted fill to GL+1.6m
5. Upper laterite blocks
6. Sandstone pavement

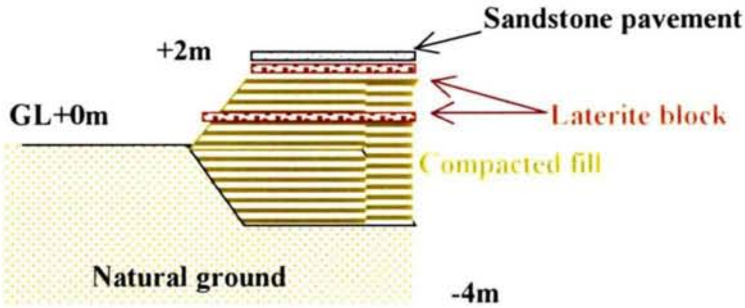


Fig.8-4 Structure of Filled Ground at Bayon

8.4 Structural stability of Northern Library and monitored behavior

North and South Libraries of Bayon are independent structures at northeast and southeast corner of the inside of the Outer gallery. The central portions of roof of both libraries have been failed and lost. Several independent masonry stone pillars support the remaining parts of roof.

It is understood visually that the Northern suffers much severer structural damages than Southern Library. Both libraries had the common feature in the failure mode of little deformation in the foundation level and distinct deformations and failures at the porch sides and roof structures. To understand the nature of the present structural stability and the emergency nature of the consolidation, we planned to perform several monitoring before and during dismantling process.

Fig.8-5 shows crack distribution of south side wall of the North Library.

Photo8-9 Gap gage to measure change of vertical opening between stone elements

Photo 8-10 Displacement Gage

Structural Behavior before Dismantling

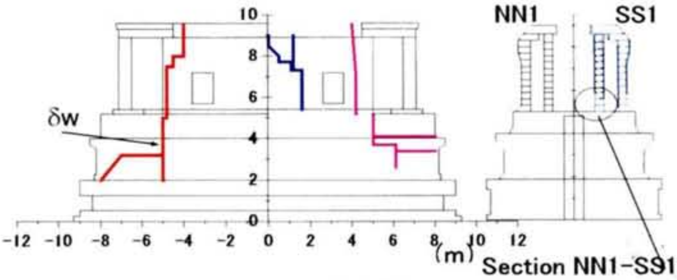


Fig.8-5 Cracks on South Side of N. Library

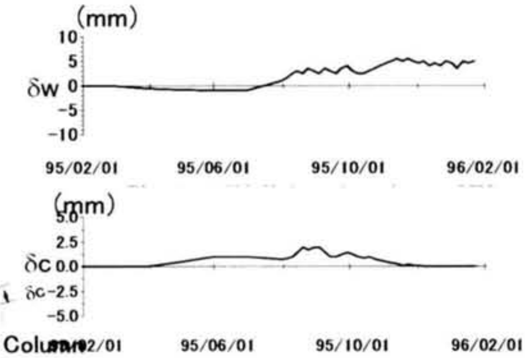


Fig.8-6 Wall gap and Column inclination

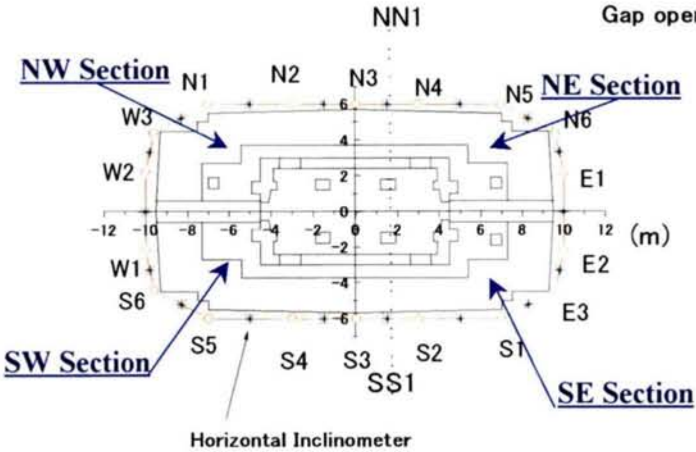


Fig.8-7 Horizontal Inclinometer at North Library Bayon

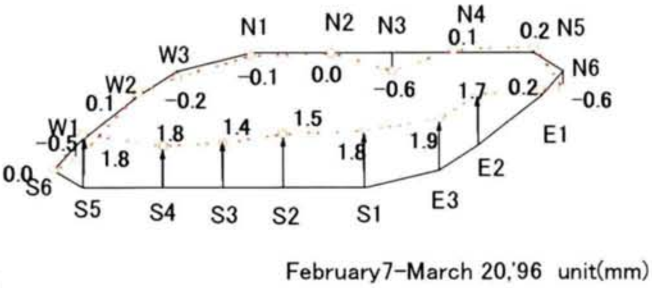


Fig.8-8 Relative heave to S6 during dismantling

To monitor of structural performance, we installed several displacement gap sensors to North Library.

Here, two examples of opening between stone blocks and inclination of column are shown. Fig.8-5 and 8-6 show the displacement gage that intended to measure separation of western side of the retaining wall from the main foundation. Inclination of column was measured by monitoring gap changes between stones shown as δc in Fig.8-5.

Fig.8-6 shows two typical results of the monitored behavior. One is the change of vertical opening gap between two stone elements at SW wall corner (δw in Fig.8-5). Another is to measure gap between column stones to estimate inclination of vertical pillar (δc in Fig.8-5). Monitoring started from March 1995 and continued to January 1996. During the rainy season from May to October, these gap openings were found increasing. However, the behavior is different each other. The wall gap had increased about 3mm during the rainy season and the column stone gap increased about 2.5mm. The difference is seen in dry season. The column gap had returned to the original position, while the wall gap had developed its tendency. Wall movement might be considered as reaching final failure. We had to terminate the monitoring by dismantling upper structures in February 1996.

It has been a conventional method to make reading once a year for monitoring structural performance. We found significant advantage of continuous measurement, which contains several important characteristics of structural behavior. Though the monitoring was stopped by dismantling, it was interesting results to understand the structural process under collapse process.
The upper masonry main structure (see Fig.8-15) was dismantled from February 7 to March 20, 1996. We planned to measure heaving response of the ground beneath the foundation.

8.5 Monitoring of heaving during dismantling

To monitor heaving of the foundation due to unloading process of dismantling, we have installed horizontal inclinometers surrounding the foundation.

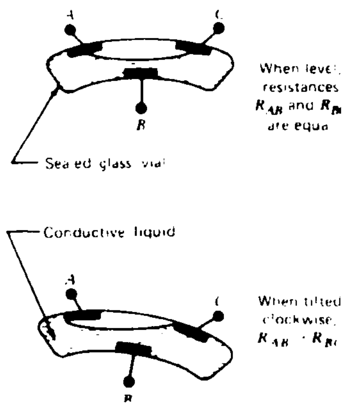


Fig.8-9a Electrolytic Level

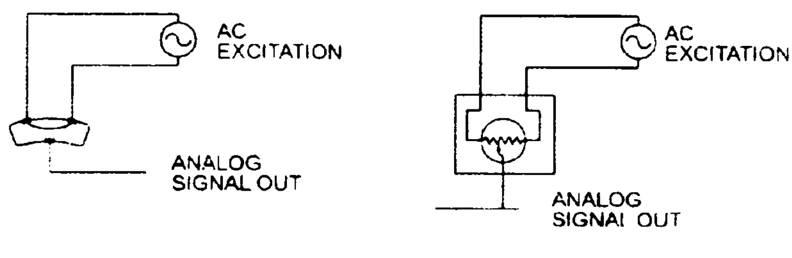


Fig.8-9b Measuring System of Electrolytic Level

Sensitivity of less than 0.3 arc second may be available of this type of the sensor.
The horizontal inclinometer is electrolytic-level type sensor that utilizes differential resistance when tilted as shown in Fig8-9a and 9b with AC current to avoid ion concentration.
As shown in Photo8-11 cement blocks were installed at 18 points surrounding the foundation (Fig.8-7).
Each cement blocks were equipped with steel threaded rod and firmly fixed with sandstone blocks.
Electrolytic sensor was set up within a rectangular alumni pipe, whose ends were fixed at the adjacent cement blocks.

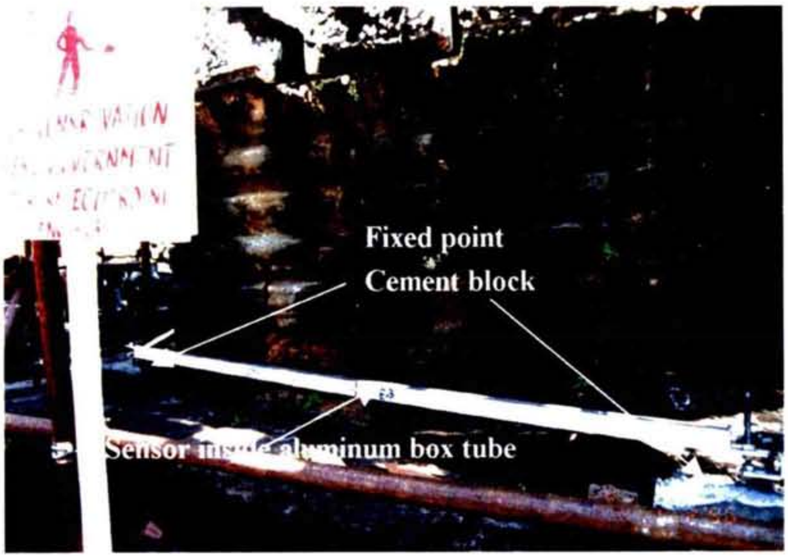


Photo 8-11 Horizontal Inclinometer

The final heaving was calculated relative to a reference point of S_0. The maximum heave was observed at south-east corner as 1.8mm and the maximum relative settlement was estimated at N3 point as −0.6mm. These resulted in the maximum uneven heave as 2.4mm.

Unfortunately, absolute settlements were not obtained because of damage of reference point for leveling. However, the heave is estimated with the differential heave as discussed below.

The amount of unload is obtained by the volumes of sandstone blocks assuming the density of sandstone as 2.7 tonf/m^3 due to dismantled and is shown in Table-8-1.

Table 8-1 Estimated unload by dismantling of North Library

	Part	Dismantled Weight(ton)	south east	north east	north west	south west	
2	south side aisle roof	7.47	3.74			3.74	
3	north side aisle roof	5.69		2.84	2.84		
	east porch (north)	1.71		1.71			
4	east porch (south)	0.00	0.00				No element
5	western porch(north)	1.68			1.68		
	western porch(south)	1.77				1.77	
6	south side wall	15.91	7.96			7.96	
7	north side wall	15.95		7.98	7.98		
8	east wall	9.34	4.67	4.67			
9	west wall	9.34			4.67	4.67	
10	nave column	5.92	1.48	1.48	1.48	1.48	
	ton	74.77	17.8	18.7	18.6	19.6	
	Area(m2)	200.	50	50	50	50	
	averaged unload(ton/m2)	0.37	0.36	0.37	0.37	0.39	

The uneven heave may be due to uneven unloading against the foundation area of 11mx17.5m or different characteristics of the underground conditions. We can divide the foundation area into four zones of south east, north east, north west, and south west part (see Fig8-7). The estimated unload values among four different zones from 0.36 to 0.39tonf/m^2.

The table 8-1 shows averaged unload stress for each zone becomes 0.37ton/m^2. Comparing the unload distribution and differential heave, the maximum heave zone of east-south corner corresponds to the minimum unload zone. Thus the differential heave implies the different heave characteristics of underground condition.

The absolute heave may be estimated by assuming the Young's modulus obtained by load plate test, which is explained later.

E=15.1MPa, Unload =370kN

$$\delta = \frac{(1-\nu^2)}{2aE}\Delta F$$

Where, δ: heave (m)

ν: Poisson's ratio (=0.3 (assumed))

a: radius of unloading area (8m)

ΔF: Unload(=0.37MN)

Thus we obtain

δ=(1-0.1)x0.37/(16x15.1)(m)=1.4x10^{-3}(m)=1.4mm

The observed differential heave is 2.5mm, which is larger than the estimated heave. However, the order of the magnitude is the same as in a few mm. In general, differential settlements are considered less than absolute settlement for uniform ground. Since there are several factors of uncertainty and we can estimate the ground characteristics of the underneath the foundation is the same as inside of the platform fill.

It was also recognized that the heave of about 2mm at south east corner compared to northwest one. The averaged inclination due to dismantling was about 2/12000=1/6000 to southeast direction. The settlement caused by reconstruction process is expected as the same amount. It is expected that the reloading effects on the foundation ground are negligible based upon this observation.

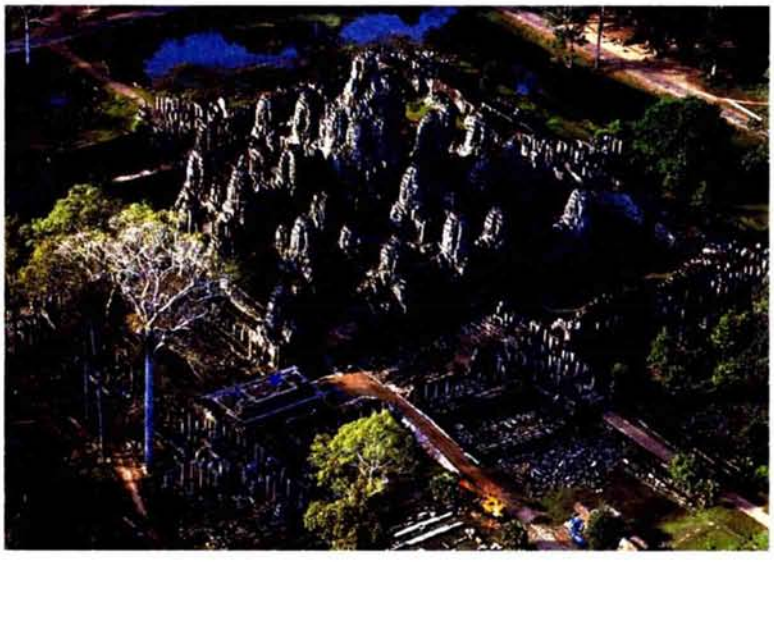


Photo 8-12 Bayon from air during dismantling of North Library(left lower corner)

8.6 Retaining wall foundation of the North Library

After dismantling upper structural elements, both sides of west and east Porch were dismantled and excavated to study the inner structure and prepared to discuss how to repair and restore the North Library.

Fig.8-10 shows the revealed retaining wall structure. The inside of the platform itself is made of compacted filled mound enclosed by laterite blocks with sandstone blocks at the outer surface. The laterite blocks are found badly weathered and there are some holes as evidences of erosion of soils by water or small animals.

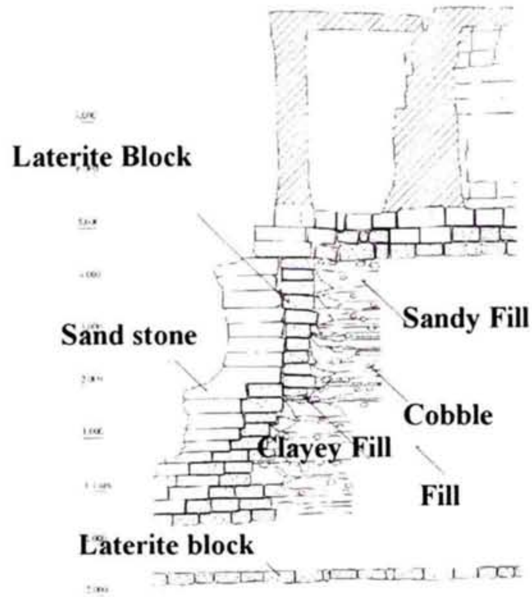


Fig.8-10 Inside structure based upon excavation of the west side of North Library, Bayon

The filled material is basically sandy material. Grain size distributions of the manmade soils are shown in Fig.8-11. The soil is sandy characteristics and is grouped into two types of sandy and clayey based upon a condition of fine contents. The clayey soil was found as the filling material at the contact area between laterite block and inside fill.

There are many cobble size materials of laterite origin within the compacted fill. However, it is not known if there is any reason to mix these materials into the fill.

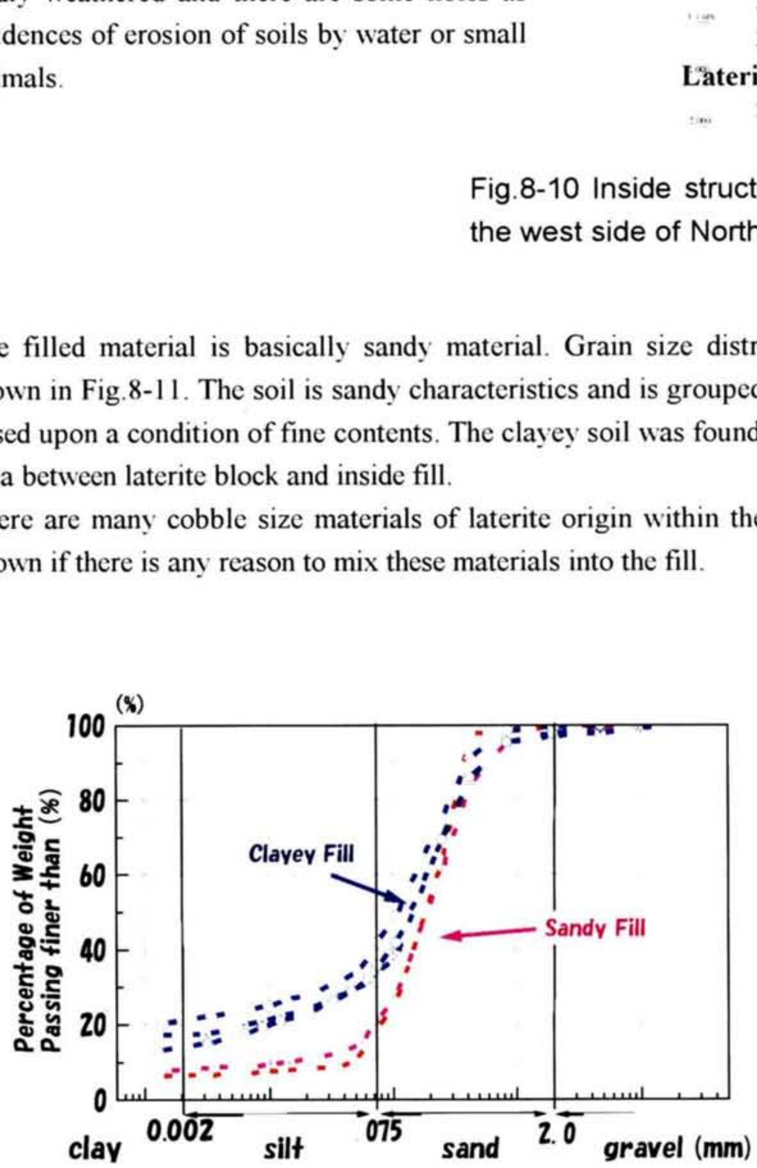


Fig.8-11 Grain size distribution of the Fill Material

Table 8-2 Geotechnical characteristics of fill inside the foundation of North Library

Field test		Laboratory test			
Plate load test (plate diameter =10cm)	p_u>1.15MPa			excavated	Sampled soil
	k_{10}=1.68 MPa/cm E=15.1MPa			(clayey sand soil)	at plate load test (sandy soil)
	ρ_d=1.797	max. dry density		1.956	1.898
	w.c.=10.99%	o.m.c.		11.7%	7.7%
Permeability	k=2.4x10^{-3}cm/sec	Grain size Analysis	gravel	2%	0%
Soil underneath the plate was sandy soil and the characteristics are shown in the right column of "Sampled at plate loaded"			sand	65%	81%
			silt	15%	12%
			clay	18%	7%
				1.2x10^{3}cm/sec	

p_u: ultimate bearing capacity, k_{10}:coefficient of sub-grade reaction

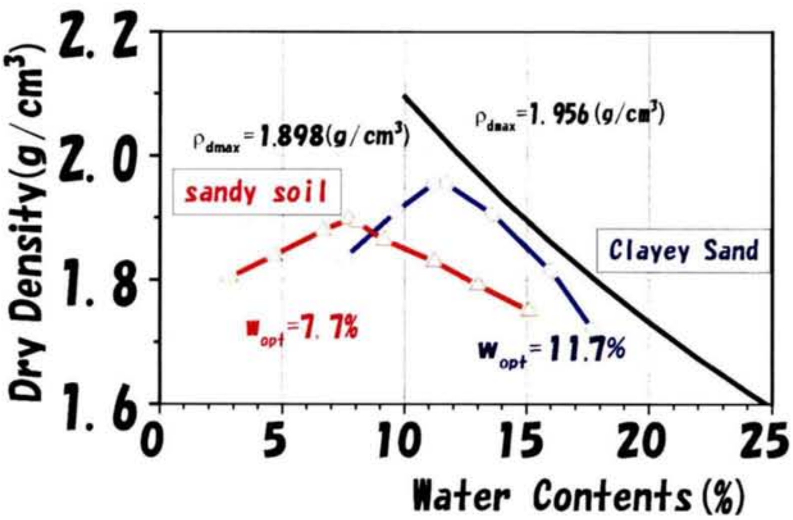


Fig.8-12 Compaction Characteristics

We carried out several tests to study compaction and related tests on these filled material, whose results are shown in Table-8-2 and in Fig.8-12.

The maximum dry density and the optimum moisture content by standard Proctor's method were obtained as ρ_{dmax}=18.98(kN/m^3), w_{omc}=7.7% for sandy soil and as ρ_{dmax}=19.56(kN/m^3), w_{omc}=11.7% for clayey soil. The permeability was 10^{-4}cm/sec for sandy and for clayey soil.

The field dry density was measured as ρ_d=17.97, which resulted in 95% of the maximum dry density. The permeability was 2.4x10^{-3}cm/sec by field test for the manmade sandy soil and 1.24x10^{-3}cm/sec for clayey soil by laboratory test.

Photo 8-13 Plate Loading Test

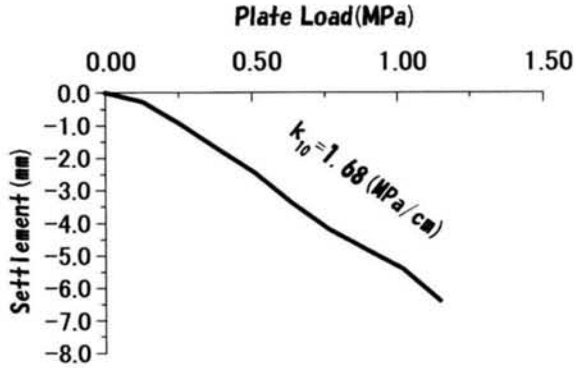


Fig.8-13 Load vs. Settlement
E=(1-0.1)x10(cm)x1.68M(Pa/cm)

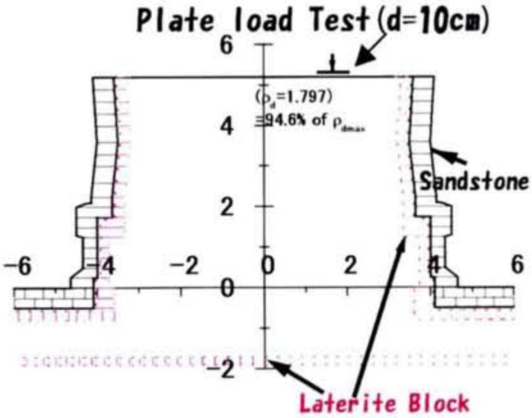


Fig.8-14 Plate Load Test Point on Compacted Fill Ground

In-situ cone penetration test was performed with handy type and the result was between 1－4MPa and 2MPa in average, which is the same value obtained at the archaeological excavation trench site at south of the North Library. We also performed a load plate test with a circular plate of 10cm of diameter. Due to the insufficient amount of loading capacity, we could not obtained any yielding stress level, which should be larger than 1.15MPa. The coefficient sub-grade reaction is 1.68MPa/cm. The Young's modulus is estimated as 15.1MPa for the filled ground.

8-7 Restoration of North Library, Bayon

Before dismantling the upper portion of the platform of the foundation, it was discussed that the dismantling of the fill should be minimized and the necessary portion was planned as in Fig.8-15.

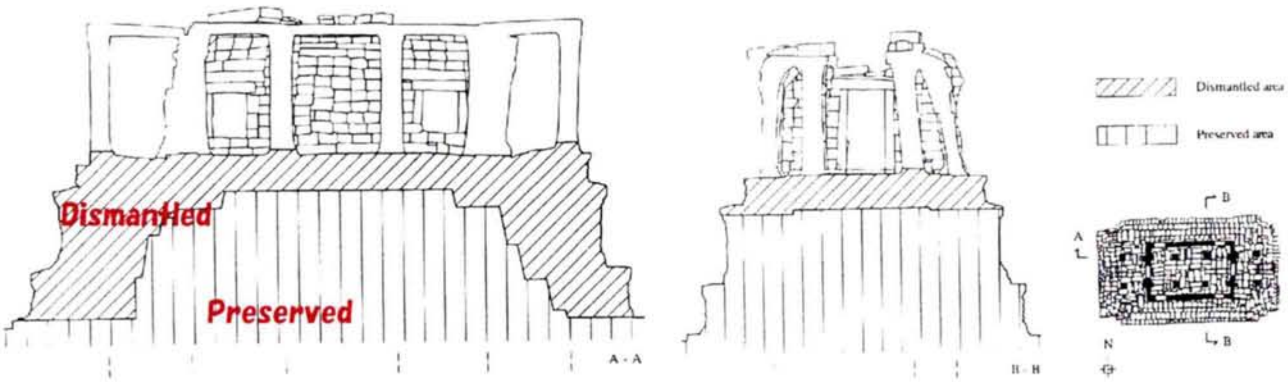


Fig.8-15 Dismantled area of fill portion of North Library, Bayon

The soil to be filled was selected as to have the same grain size distribution as the existing one. It was found that this was satisfied if the following two kinds of materials mixed with a mass ratio of 9:1.

Commercially available sand and Clay (produced nearby Bayon, North Gate)

We had tested several kinds of fill material including soil cement mixed soil and slacked lime mixed soil. We selected the fill material through a comparative study of the grain size adjusted soil, adjusted soil mixed with cement, and adjusted soil mixed with slacked lime.

Among several requirements of geotechnical characteristics, it is considered the most important characteristic is the bearing capacity of the fill beneath the columns that should support the roof structures.

The largest expected load stress at the base of a column, which includes the missing upper roof, is 0.3-0.4MPa including the weight of column (0.6mx0.6mx3m) itself. The required compression strength is about 1MPa with F.S.=2-3. If we assume the allowable settlement as 0.5cm, the minimum value of coefficient of subgrade reaction is k=0.6-0.8MPa/cm. The corresponding Young's modulus is 32-43MPa. Table 8-3 shows required mechanical characteristics of filled ground.

Table 8-3 Requirement of mechanical characteristics of filled ground

	Estimated condition	Considered parameter and Required value	
Bearing capacity	0.3-0.4MPa/0.6x0.6m^2	Unconfined comp. strength	q_u>1MPa(SF=1)
Allowable settlement	0.5cm	Young's modulus	E>32-43MPa

8-8 Selection of fill material for embankment of North Library

Simple mixture of sand and clay does not satisfy the compression strength. Soil mixed with cement or slacked lime were found satisfactorily results if the amount of the additive is controlled. If we compare cement mixed and slacked lime mixed soil, slacked lime is considered much more stable than cement from geo-chemical point of view (see foot note).

Mechanical characteristics improve in proportion to quantity of slacked lime added, which accompanies with increase of cost. We tried various ratio and concluded to adopt a standard mass ratio of sand:clay:slacked lime=1:0.1:0.1 based upon the following tests.

It is well recognized fact that slacked lime mix soil improves its performance when it is kept as it is for some period before compaction (curing process). The effect is known as "aging". The aging effect varies with quality of slacked lime. It depends on how much quantity of slacked lime is contained in commercially available slacked lime. The effect of aging for slacked lime is due to accelerate the chemical reaction of hydration of quick lime to slacked lime. If the quick lime remains, the volume expansion in the process of hydration causes failure of soil structure that results in weakening the mix soils.

Based upon preliminary tests of unconfined compression strength of mixed soil with the locally available slacked lime, there is little difference between soil mix soils with aging period of 3hours and 24hours. We concluded three hours of aging period for the local slacked lime is sufficient after mixing

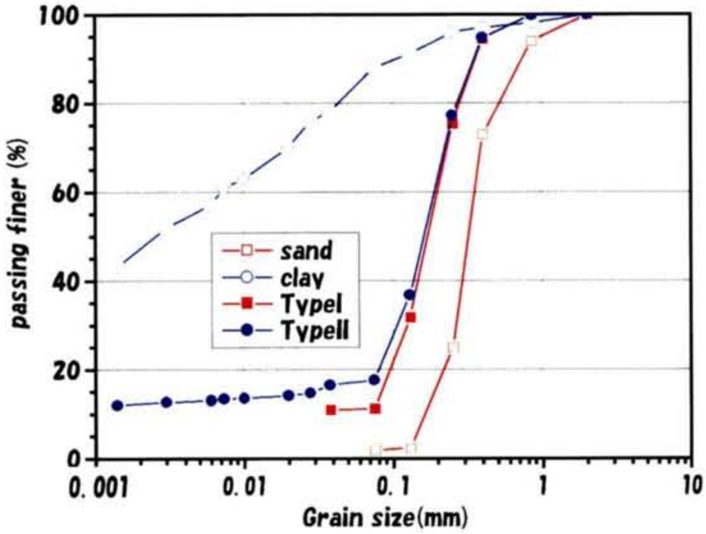


Fig.8-16 Grain Size distribution of fill material

with soil. Two types of mixed soil are used as shown in Table8-4 and their grain size distribution curves are shown in Fig.8-16. Most part of the fill of the foundation was made of compacted sandy fill material (Fill Type I).

Table8-4 Selected Fill Material

	Mass ratio			Water contents	
	Sand	Clay	Slacked lime	At mixing	(At compaction)
Fill Type I(sandy)	1.0	0.1	0.1	8.2%	7.0-7.2%
Fill Type II(clayey)	1.0	0.2	0.1	8.5%	7.2-7.5%

* Hardening mechanism of slacked lime

The hardening of cement is caused principally by hydration of CaO resulting slacked lime

$CaO+H_2O \longrightarrow Ca(OH)_2$

Slacked lime becomes calcium oxide (lime stone) through carbonation.

$Ca(OH)_2+CO_2 \longrightarrow CaCO_3+H2O$

The resulting lime is more stable than slacked lime, which will deteriorate by carbonation (also known as neutralization process of cement/concrete material.

The slacked mixed soil increases strength with time because of the gradual chemical process of carbonation. These specimens were kept under curing and were tested at 0, 14, 28, 90, and 180days of aging period. At every time, three specimens were tested to obtain unconfined compression strength.
The slacked mixed soil increases strength with time because of the gradual chemical process of carbonation.

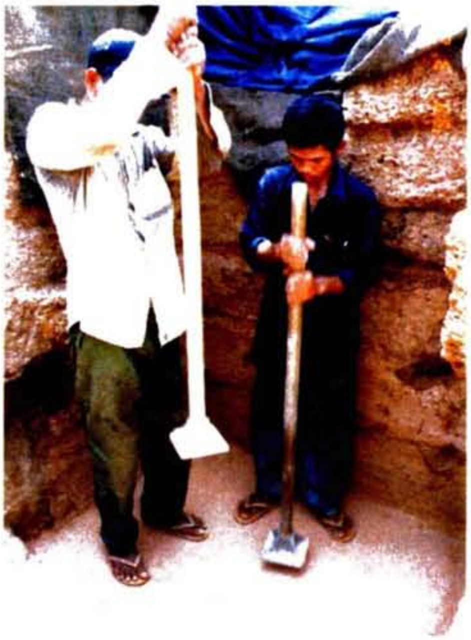


Photo 8-14 Manual compaction using "*elephant foot*".

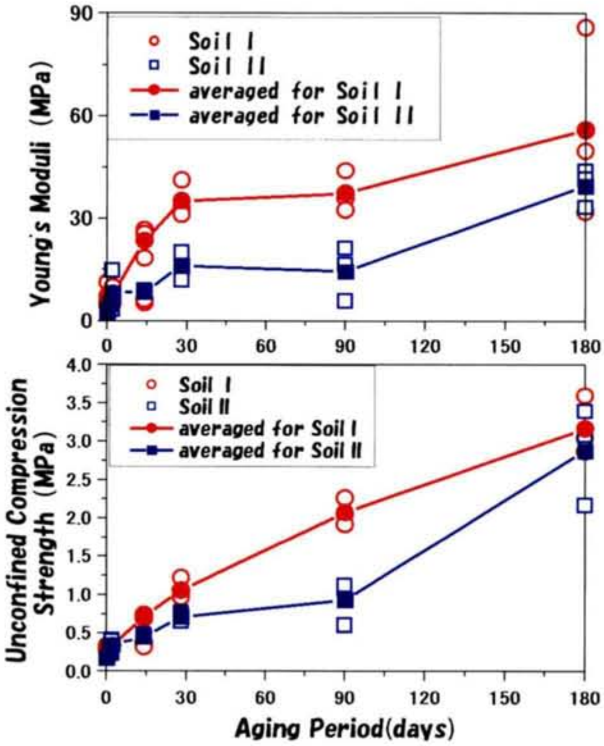


Fig.8-17 The increase of Young's modulus and unconfined compression strength with time

These specimens were kept under curing and were tested at 0, 14, 28, 90, and 180days of aging period. At every time, three specimens were tested to obtain unconfined compression strength. The results are shown in Fig.8-17 for the increase of Young's modulus and for unconfined compression strength.

The increase of the strength is more or less proportional to aging period; on the other hand, the increase of Young's modulus rather concentrates in the earlier period. The increase of the strength depends upon the chemical reaction of carbonation. The test specimens were touched by air, whose carbon oxide(CO_2) could easily infiltrate into specimen. Since it is difficult for air to reach to field compacted sand inside the fill, the carbonation process might be much delayed than the laboratory test. Never the less, the available strength of slacked lime mixed soil can reach as high as 2.5 to 3.5MPa with Young's modulus of 40 to 60MPa. Since the Young's modulus required corresponding 0.5cm of 0.6x0.6m column is 32-43MPa, the measured values are found greater than the required modulus.

8. 9 Field Process of Compaction

Field process of compaction is summarized as follows.

1. **Preparation of fill material:** Commercially available sand is first sieved to remove larger particle than 2.0mm. The sand material is then exposed to sun to be dried to lower water contents than 0.5%. Clay material is excavated near North Gate of Angkor Thom. After crushing and powered by hammer, the clayey material is dried to lower water contents below 3%. The dry sand and clay materials are packed within plastic bag covered by plastic sheet to protect from wetting.
2. **Slacked lime:** The commercially available slacked is obtained through a local shop to confirm to keep the constant quality. The slacked lime is sieved to avoid larger size material more than 2.0mm. The same packing method is applied as soil material.
3. **Water:** Water is brought from Siem Reap River and left over one night in drum can to let foreign materials sink in the bottom.
4. **Mixing and Curing:** Two types of fill materials are prepared according to the required filling portion. Mass ratio of each materials are as follows.
   Mixed Fill Material No1.: sand : clay : slacked lime : water = 10:1:1:1
   Mixed Fill Material No2.: sand : clay : slacked lime : water = 10:2:1:1
   Water contents for each material are about 7.5% and 8.0% respectively.
   Electric mixer is used to blend the materials. After mixing, the fill materials are left over under sunshade for curing. The period must be no more than 3days.
5. **Joint filling (Mixed Fill Material No.2):** After sandstones and laterite blocks are mounded outer side and inner side respectively first. No filling material is supplied between sand stones. However, spaces between sandstone and laterite block and between laterite blocks are arranged about 1-2cm and filled with fill material No.2. The filled material is compacted with tamping rod. The fill material No.2 is also applied to boundary of laterite block and inner fill.
6. **Inside platform of compacted fill:** The surface of the existing or compacted fill is to be scratched with any cutter to make rough surface to become better contact between the finished and new filling. Mixed fill material No.1 is spread out on the fill yard of the platform with thickness of about 10cm. The initial compaction is to be by human foot, followed by tamping the elephant foot (see Photo8-36 tamping plate: $10 \times 10 cm^2$) for 5 to 10 times until no more compaction is realizable.
7. The fill shall be covered with plastic sheet to keep it from drying for one day. Next day, we tested the fill with small cone penetrometer to confirm the cone resistance larger than $15 kg/cm^2$ (corresponding to unconfined compression strength of about 0.3MPa).

8-10 Completion of restoration


Photo 8-15 Before Restorations (1)


Photo 8-16 Before Restorations (2)

Started in November 1994 JSA had continued their efforts to restore North Library of Bayon and took about 1500 days to complete the restoration work in September 1999.

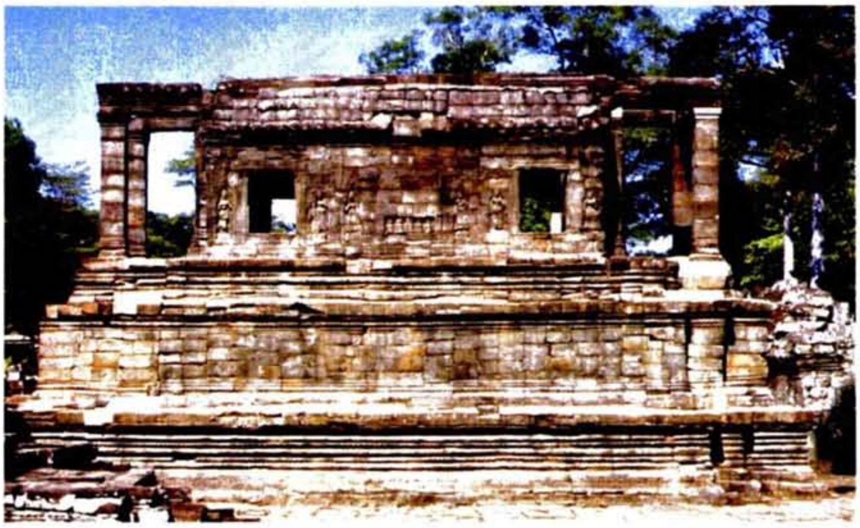


Photo 8-17 After Restorations


Photo 8-18 Celebration of Completion of Restoration Work

8.11 Conclusion

In the restoration work of the North Library at Bayon, geotechnical engineering was one of major disciplines to be considered. One of the problems was how to keep authenticity as ancient Khmer culture.

Based upon the slope failure experience, French team had to introduce a hidden retaining wall of reinforced concrete inside the fill at Bapuhon. They extended this design concept to restoration work to Terrace of King Leper.

Photo 8-19 Arial view after completion of restoration of North Library from north.

The height of the platform made of soil North Library is about 5m, which is the same height where French team experienced failure at Bapuhon. JSA adopted another way of increasing soil characteristics by mixing slacked lime.

The development of strength of slacked lime mixed soil is slow compared with cement mixed one. One of the disadvantages of slacked lime mixed soil is to take longer period to confirm the required mechanical characteristics.

The curing effect was confirmed by testing at various aged period of cores that were sampled at the initial stage of filing platform.

So far, the results of soil mixed with slacked lime were satisfactory. However, it should be observed with care in the future of long period under severe climate conditions.

8.11 Reference

JSA(2000),"Report on the Conservation and Restoration Work of the Northern Library of Bayon, Angkor Thom, Kingdom of Cambodia," JSA, Tokyo, pp.95-102

9 Laterite as a construction material in Angkor

9.1 Laterite

Laterite soils are essentially product of tropical or subtropical weathering. The name of laterite comes from a word in Latin. The Latin word "*later*" means "brick" and a suffix "*ite*" shows the word as geological term as in "*Granite*" and "*Ammonite*." (M.D.Gidigasu,1976)

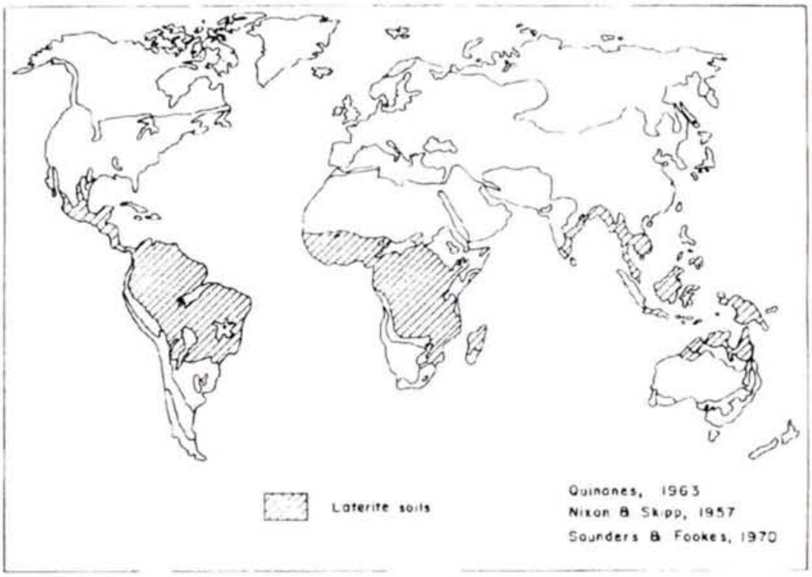


Fig.9-1 Distribution of Laterite (M.D.Gidigasu, 1976)

The simplest definition of laterite or lateritic soil is "ironstone conglomerate" (Visser, 1965).

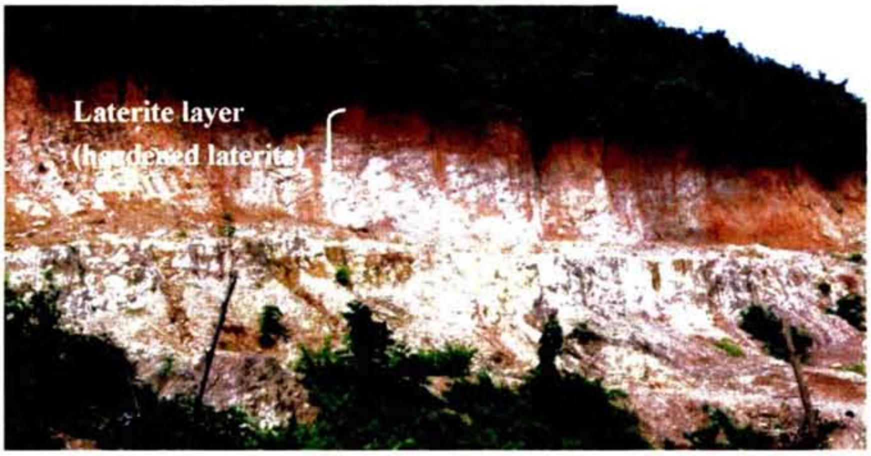


Photo 9-1 Laterite layer

During the weathering of mother rock under tropical conditions of high temperature with high humidity, aluminous silicates, the silica, alkalis, and alkaline earths are dissolved and removed in solution due to acidic character of water in the tropical region, while the alumina and ferric oxide become dehydrated and remain behind. The distribution of laterite is shown in Fig.9-1, which corresponds to humid and high temperature regions.

Lateritic soil is decomposed rock yellow and brown in color and often soft enough to cut by ion knife. Once exposed to the air, the soft lateritic soil becomes harden due to oxidation of ion and aluminum.

Photo 9-2
West
causeway
Angkor Wat

In Angkor monuments, laterite blocks were used fundamental construction material as structural element covered with sandstones with relief on the surface as shown in Photo 9-2.

9.2 Weathering of laterite block

In Angkor monuments, we could find various phenomena caused by the weathering of laterite blocks.

Photo 9-3
Decayed laterite blocks
(Foundation of Bayon temple)
desharpened edges
and surface weathering

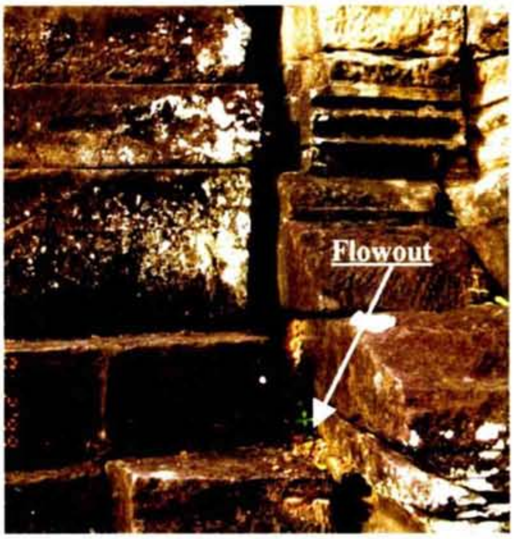


Photo 9-4
Flow out of decomposed laterite
(South Library, Bayon Temple)

Typical example in Photo 9-3 is de-sharpened edges of laterite blocks and volume of block is found decreased. It is shown in Photo 9-4 that decomposed laterite block inside the sandstones flows out through an opening between sandstones.

9.3 Inclination of water front structures

Photo 9-5 Inclination of embankment along moat of Angkor Wat

A typical example of inclination of water front structure is shown in Photo 9-5. The inclinations are usually found towards waterside. These phenomena are found not only at Angkor Wat but also every structure near waterfront. Some says this is creep movement of slope stability

Photo 9-6 Leveling of steps of embankment at Srah Srang (see the location of Srah Srang in Fig.2-3)

There is a pond named "Srah Srang," whose embankment steps were measured with leveling. Three sections were selected along east side at northeast corner of the pond and the results of leveling are shown in Fig.9-2.

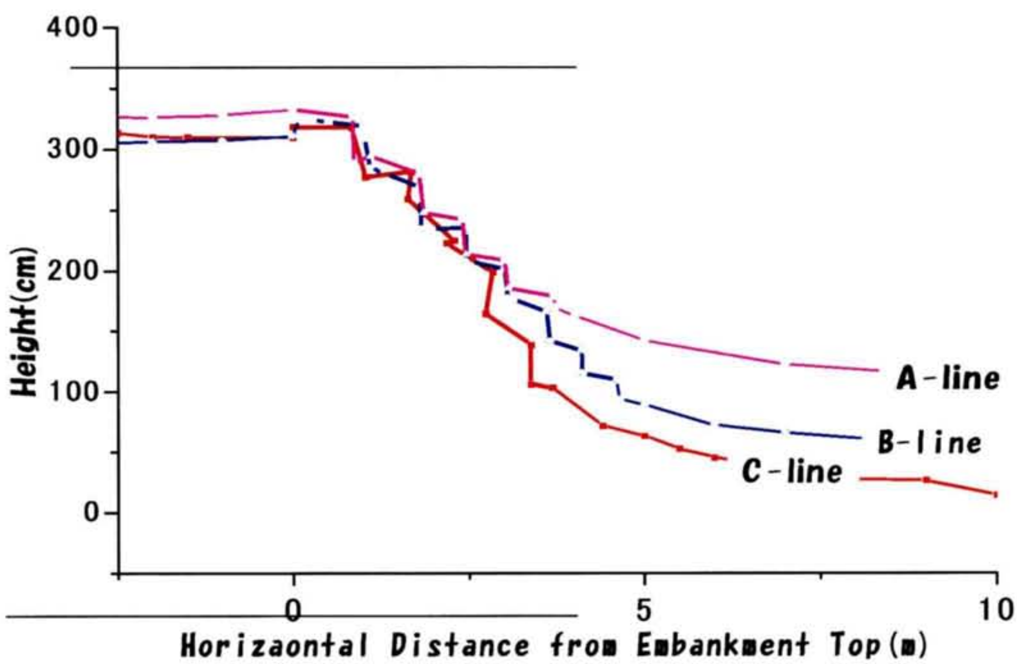


Fig.9-2 Leveling of surface of step stones at Srah Srang

As shown in Photo 9-6, A-line is the nearest one to the corner. Among three sections, the top of the embankments of three lines are almost the same, the lower levels of the three lines are different each other. It is expected that the mechanism to cause the inclination phenomenon does not include sliding of the slope failure. If the inclination is related with sliding shear failure, the top level of the embankment along A-line becomes lower than that of C-line.

Archaeological Unit of JSA, had performed trench excavation at the west side of North Pond, Prasat Suor Prat, where the embankment section was disclosed as shown in Fig.9-3. Fig.9-4 shows imaginary reconstruction of the original embankment at the side by the archaeological unit, J.S.A.

The steps of the embankment were made of one bottom stone and 13 step blocks of laterite stones. The bottom stone was embedded in the foundation trench at 4.5m from the ground surface.

The top block is found inclined towards waterside, however, the trend is not always the same.

From the bottom of the pond, the slope with an inclination of about 40 degrees was constructed by compacted soils with surface covered by laterite blocks. Apparently, laterite blocks around GL-1m have significant changes of shapes of blocks. Some are broken into a few pieces. The broken pieces were further weathered and the surface of the stone became dissolved and blocks became very small.

The present level of water in the pond is about GL-1m in rainy season and becomes lower in the dry season. It is easily anticipated that the fluctuation of water level makes severe change of temperatures of the block surface, which contributes to accelerate weathering at this level.

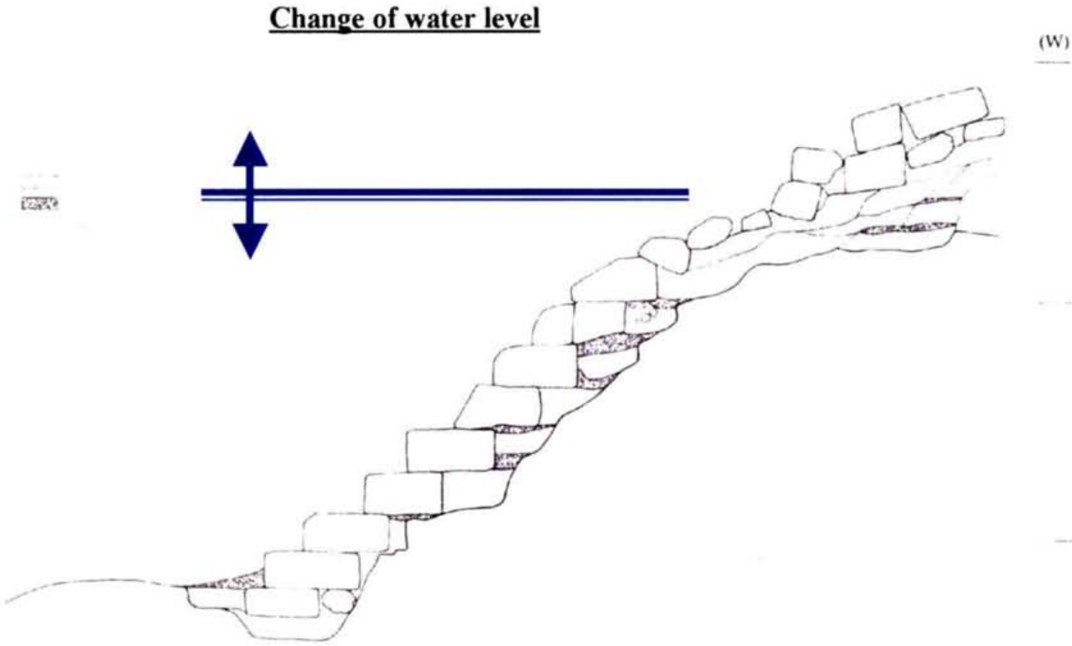


Fig.9-3 Section of the existing state of shore protection work at the embankment of North Pond, Prasat Suor Prat (JSA Report(1998))

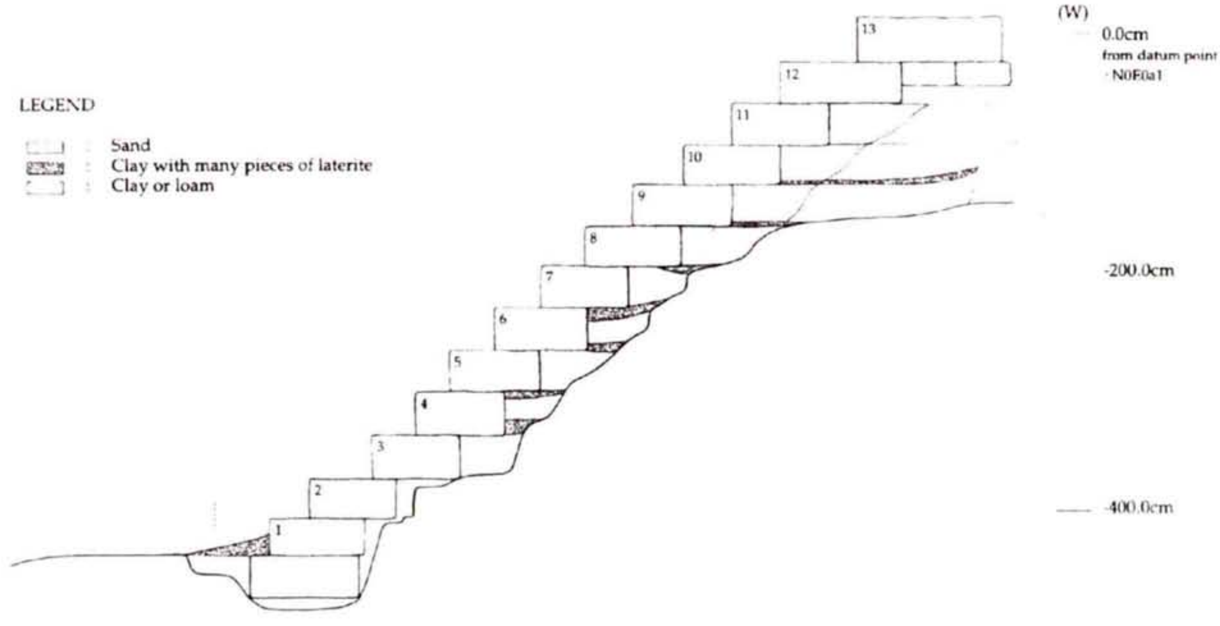


Fig.9-4 Imaginary Section of the original state of shore protection work at the embankment of North Pond, Prasat Suor Prat (JSA Report(1998))

The inclination of the step blocks towards pond side will take place if the lower block deteriorates earlier than the upper blocks

The decay and weathering of laterite blocks are one of major contributions to deteriorate the masonry structures in Angkor.

9.4 Quality of laterite and P-wave velocity

The quality of laterite blocks depends upon several factors. If the quality is poor, the laterite may have small strength and easy to decay. Photo 9-7 shows old used laterite block, which has many voids in the surface. The void was originally filled with such materials as kaolin and considered eroded out during weathering process. The new laterite should be checked and selected to obtain good quality material to be used.

Photo 9-7 Old laterite block

Photo 9-8 New laterite block

Sampling specimen may be tested for unconfined compression test. However, laterite is a natural product and it varies from piece to piece. If technician experienced, he become to identify which laterite block is in good or insufficient quality.

We had a chance to compare one group of used laterite and new materials grouped into two kinds of category by masonry expert as follows,

New material good quality	A
New material insufficient quality	B
Old used material	C

We measured P-wave velocity by ultra-sonic measurement device. The results are shown in Table 9-1 and plotted in Fig.9-5. Photo 9-9 shows sensors of P-wave measurement and laterite of new material grouped into B.

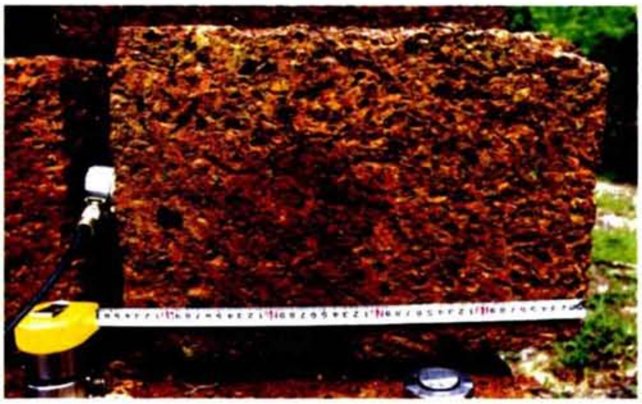


Photo 9-9 P-wave measurement for group B

Table 9-1 Variation of P-wave velocity for laterite blocks in Angkor

	P-wave velocity of laterite blocks(km/sec)		
	new material		used material
Sample	A	B	C
	good quality	insufficient quality	
1	1.78	1.08	1.44
2	1.80	1.43	1.57
3	1.62	1.17	1.42
4	1.39	1.19	1.52
5	1.57	1.57	0.96
6	1.41	1.52	1.57
7	1.81	1.26	1.52
8	1.90		1.26
9	2.04		
10	1.35		
11	1.85		
12	1.98		
13	2.02		
average	1.96	1.32	1.41
the lowest	1.35	1.08	0.96
the highest	2.04	1.57	1.57
standard variation	0.24	0.19	0.21

It should be remembered that among samples of class B, there are some samples that could not be measured due to excessive decay of the pulse.

Though, the classified group by expert corresponds well to the measured P-wave velocity.

In average, the p-wave velocities for each group are

Good quality laterite 1.96km/sec

Insufficient quality laterite 1.32km/sec

Used laterite 1.41km/sec.

The old used laterite showed a little faster velocity than the insufficient quality.

If the P-wave measurement is used for classifying quality, a threshold value of 1.75km/sec may be used for safer side. Any laterite material with P-wave value less than 1.75km/sec or un-measurable may be classified into insufficient quality laterite.

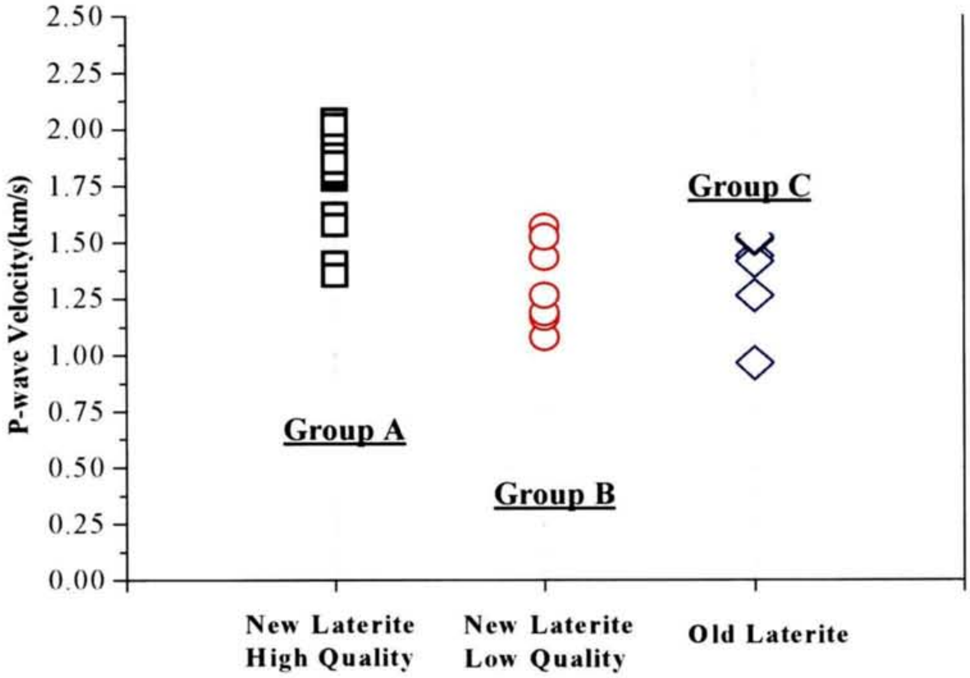


Fig.9-5 Distributions of P-wave velocities for three groups of laterite material

9.5 Conclusion

In this chapter, the author explained the basic characteristics of laterite, which was one of the basic construction materials in the construction Angkor monuments.

The laterite is a product of chemical weathering of rock under tropical conditions. Chemical process in the tropical region is to accumulation of higher contents of iron oxide and Aluminum oxide in the upper surface of ground. Iron oxide and Aluminum oxide works as strong bond among sands and gravels.

The laterite blocks were used as structural member covered by sandstone block with relieves on its surface. However, Several examples of structural failure resulted by weathering of laterite were shown in the chapter.

The inclination of structures at shoreline towards water was caused by decay of laterite blocks.
The P-wave velocity was measured for three groups of laterite classified by masonry expert. The velocities correspond well with each group and may be used to check the laterite blocks for use.
The author thinks the decay of the laterite had resulted in one of the major causes of structural failure of Angkor monuments. Accordingly, we see the unique phenomena like the inclination of structures towards waterside in the region.

9.6 References:

JSA(1998), Annual Report on the Technical Survey of Angkor Monument 1998, pp.161-195
M.D.Gidigasu (1976)"Laterite Soil Engineering", Elsvier, p.3
A.D.Visser (1965) "Dictionary of Soil Mechanics", Elsvier, p.108

10 Suggestions on safeguarding Angkor monuments

The author realized that the geotechnical study is one of the new fields in Angkor not only for the monuments to be preserved but also for civil engineering purposes in Cambodia. The knowledge of laterite and lateritic soils as the basic construction material are helpful to develop civil engineering practice in this region.

In this chapter, I want to summarize the results as suggestions on safeguarding monuments in Angkor in geotechnical engineering. I also added a few problems of geotechnical engineering that were out of the scope in this paper but necessary to consider safety of the Angkor region from geotechnical view points.

10.1 Causes of structural failure identified in the report of Tokyo Conference

The basic concept of the structural failure is described in the Report of Tokyo Conference as the following five categories.

1. Abandonment of the site and damage caused by vegetation
2. Deterioration of hydrographic system
3. Rainwater runoff and drainage system on the monuments
4. **Structural design of high masonry upon compacted soil ground**
5. **Effects of the expansion/contraction of the subsoil**

Among five categories, two of 4 and 5 are in the field of geotechnical engineering.

10.2 Clarified characteristics of the causes of failure of structures in this research

Some of the problems on these categories have been solved, however, the others remains as described in the following.

The problem 4 could be further divided into two groups of foundation problem and slope instability.

The foundation problem includes the interaction problem of masonry and ground system. In this foundation problem, we have experienced two different cases. One is structures on flat ground condition. Another is structure nearby water or pond.

Structure on flat ground condition:

In the flat condition, say, North Library of Bayon at Angkor Thom, there is little problem on the foundation of ground concerned. That is no large differential settlement that might have caused the damage of the upper structures. However, even though flat condition, if the laterite became decayed, the upper structures became very easy to be displaced and resulted in structural failure. During dismantling process of the embankment of the North Library of Bayon, we have performed a plate-loading test, which resulted in more than 1.2MPa of strength of bearing capacity. The estimated vertical stress anticipated on the foundation ground at Central Tower of Bayon is about 0.45-0.8MPa. The bearing capacity of the filled ground is large enough to carry the Central Tower Load.

Embankment structure:

On the other hands, embankment of compacted soils has become very unstable if the laterite blocks inside the embankment decayed. If the laterite blocks decays, the filled soils become unstable against water and flow out. This is clearly shown at the North and South Library of Bayon, where the middle and upper portion of the foundation at the east and west sides were heavily damaged and no damage is found at north and south sides of the foundation. If the soil itself is the problem, north and south sides should have been also deteriorated.

Some of the basic characteristics have been studied and presented in Chapter 5 and 6, it is not clear the slope stability of *Baphuon* mound with 20m in height and 40 degree of slope inclination as discuss in Chapter 2.3.

Structures nearby water or pond and Laterite blocks:

Two different mechanisms were studied in this paper as,

1 The embankments of the North and South Ponds were displaced towards ponds due to nearby structures of N1 and S1 Towers. These structures have been also displaced as the ground deformed.

2. Laterite blocks are less durable than sandstone materials and were shown in Chapter 9 that the decay of laterite blocks has caused the inclination of the structures nearby shoreline towards water pond.

There should be noted that other possible mechanisms related to cause instability were fond in the embankments of moat of Angkor Wat.

3. There are soil mounds at several locations at the foot of the embankments in the moat. The soil mounds have been formed due to flow out of soils of embankment through hollow pipes in the embankment. Due to this piping, large voids have been formed within the embankments. We can see holes on the surface of ground behind the east embankment of north moat at the west causeway. We also could see these voids beneath the sandstone blocks of west embankments along the moat around the west causeway of the Angkor Wat, where the many tourists enjoy to stop and walk. Since every heavy rain induces the flow out of the soils of embankments, the embankment is suffering impending failure. The studies of voids by excavation and countermeasures to keep their safety against failure are considered urgent matter not only to protect structure itself but also the tourists for Angkor.

4. The east side embankment along the south moat near the west causeway was found failed after the heavy rain during September 1997. The author had visited the site a week after the failure taken place. There was neither trace of piping nor hole on the ground surface behind the embankment. The failure was caused not by piping but probably by increase of water level in the embankment. The shortage of surface drainage behind the embankment during heavy rain induced to infiltrate the water into the embankment have resulted in the failure. The drainage pipes that leads surface water to the moat should be designed to have the capacity of drainage against the heavy rain of 60mm/hour and 180mm/24hours.

Laterite blocks:

Laterite block was already identified as weak material in the report at Tokyo Conference.

Laterite is a heterogeneous geo-material that contains ion and aluminum oxide and shows very strong character if these chemicals become bondage among particles of laterite.
Due to the heterogeneity, mechanical characteristics of laterite vary from very strong to rather fragile or from endurable to weak against weathering. Since the water in Angkor area is pH=5, the acidic condition with water movement around Laterite blocks make leaching cation from the laterite, which accelerates weathering of the blocks.

As found in Prasat Suor Prat, the laterite blocks have been weathered, weakened, and broken into several pieces after several hundred years from construction.
It was thus confirmed that the major structural damages have been resulted from decay of laterite blocks. Since these laterite blocks have been used as the structural elements of foundations, the weathering or decay of the laterite blocks directly causes foundation displacements and results in failure of the upper masonry structures.

Effects of the expansion/contraction of the subsoil

Settlement gages were installed at three depths at N1 Tower, Prasat Suor Prat and monitored from 1997 to 1998 as described in Chapter 9. It was observed shrinkage of the ground took place in dry season and expansion in rainy season. The shrinkage corresponds to drying process and the expansion corresponds swelling of the soils.
Two mechanical reasons of expansion and contraction are considered. One is effective stress change caused by seasonal change of water level. Another is change of suction pressure in soil. It was confirmed that the expansion and contraction of the ground are in cyclic nature. The estimated expansion/contraction based upon measured relations with water level and suction pressure were 8.5mm and 16.7mm for draw down of water level of 5m and 10m respectively.
The long term effects is not clarified yet and should be kept on monitoring in the future.

10.3 Newly identified cause of failure

Strong wind

As shown in Chapter 10, strong wind is found as another cause to destroy the masonry tower structure in Angkor.
Therefore, the sixth cause should be added as
6. Effects of strong wind that cause displacements of stones and accelerate fallout of stones from Central Towers.

Water environment

Underground water is found lower and lower recently in Siem Reap city. The trends may be accelerated by increase of usage of water by Hotels through tourism. The lowering of underground water table is anticipated to cause settlements/uneven settlements of the masonry structures in Angkor.

10.5 Suggested research topics in geotechnical engineering

The remaining problems on preservation of Angkor monuments in geotechnical engineering are as follows.

1. Characteristics of compacted fill including slacked lime mixed soil
2. Slacked lime mixed soil
3. Decay of laterite blocks and protective measures against decay
4. Initiation of cracks of sandstones and falloff process at Central Tower of Bayon
5. Threshold limit of allowable settlement to safeguard the masonry structures in Angkor

Characteristics of compacted fill

Lateritic soil is used as filling material in old Khmer. Khmer engineer made a very steep angle of pyramid of soil. The embankment of about 40 degrees with a height of 25m of *Baphuon* temple is a very unique example. As French people experienced, they failed to make the same slope monument.
In making very steep slope, we may have some choices.

We may stick to the original methodology of old Khmer. In this case, we must study the old method in the lost world. Old Khmer engineer might have added some materials, which was, however, disappeared at present. Or, we may use concrete retaining wall as French adapted to reconstruct *Baphuon* temple. We may introduce modern technology of geotextile to reinforce soils. We may add slacked lime with fill soils.

Characteristics of compacted fill should be studied to understand stability of high angel slope of *Baphuon*. Test embankment with instrumentation to monitor the performance is the best solution to know the problems. Laboratory tests are necessary to understand the behavior of the embankment.

Slacked lime mixed soil

When we made reconstruction of a foundation embankment of Library, we found the compacted soil does not give enough strength to support the upper structure. We used slacked lime mixed soil to reconstruct the foundation of North Library of Bayon Temple. The slacked lime showed high aging effects, which took slow chemical process of carbonation. Because the final product by carbonation of slacked lime is limestone that is considered very stable material in general environmental.
The general mechanism of chemical process is understood as carbonation. The chemical reaction is rather very slow. After 180days, the tendency of increasing strength is found continued. Since it is anticipated the tension strain at failure may become smaller as the strength is increased. The massive embankment may need to be reinforced at some local area where tensile deformation may prevail.
A research study on accelerating chemical reaction of carbonation may be needed for easy application of slacked lime mixed soil in the restoration work in Angkor.

Laterite blocks

Since it is inevitable that the laterite block shall be weathered in longtime range, we may have three alternatives. One is to use the laterite blocks as has been in the past. In this case, we have to renew the blocks if weathering advanced. Another choice is to replace some other material as a core material decorated with laterite on the surface. Third alternative is to cover some measures on the surface of the new laterite blocks to be used, which will protect or at least delay the weathering process.
Study of the decay or weathering process of laterite is needed in the future.

Initiation of cracks of sandstones and falloff process at Central Tower of Bayon

The author has proposed the cracks of sandstones and vertical opening above the stones are found and process of falloff of pillar elements. It could be confirmed that the behavior of crack opening/closing caused by temperature and wind.

Threshold limit of allowable settlement to safeguard the masonry structures in Angkor

The effect of contraction/expansion of soils upon settlement of ground was shown through measured data. How much settlement/heaving causes any damage of masonry structures in Angkor is to be studied.

10.6 Monitoring of monument behavior

The traditional monitoring to observe settlement or displacement of the monuments has been to measure a few times per year and to obtain long year trend of the movement. However, it becomes rather easy to perform precise measurement with high frequency intervals at any place. Since no commercial electricity was available in the monument site in Angkor, we have installed special type of data logging system that can make every one hour measurement and store the measured data as long as one year. Or we have installed solar battery to supply electricity to charge the battery that runs data logging system.

It was found that peculiar creep movement of inclination of walls at Prasat Suor Prat was recorded after a heavy rainfall in 1997. Gap opening between stones are shown basically due to shrinkage or elongation of stones by monitored data of temperature, strain of stone surface, and gap opening. Very strong winds were realized to cause sudden displacement of gap opening between stone blocks. These records were never realizable if we had followed the conventional method of monitoring.

It is essential to arrange monitoring system that enables to perform continuous, precise, and a long-term data logging system to catch any possible change that often comes all of sudden.

10.7 "*Anastolosis*" and consolidation measures from the view points of geotechnical engineering

"*Anastolosis*" is introduced in Chapter 4 and has been approved as an international standard of conservation of world heritage. There are many unsolved problems of geotechnical engineering in Angkor, if we have to follow the "*Anastolosis*."

As shown in Chapter 2.3.2, the soil embankment in Angkor was very steep with slope angle of about 40degrees. French group tried to make the original embankment with compacted sand, but failed twice. French had to have modified the construction design introducing concrete retaining inside the embankment. A sandwich structure of alternation of sand and clay may be much more stable than the uniform soil structure.

It is not known how the ancient Khmer engineer made such steep fill. This is a good technical question comparable to how the Egyptian made the Pyramid with stones.

JSA also had the same kind of problem when they repair North Library of Bayon in Angkor Thom. They did not use concrete but introduced new filling material of "*stacked lime mixed soil*" as foundation embankment. Concrete decays under acidic environment, which is known as neutralization process of chemical weathering by carbonation.

Stacked lime mixed soil is a new approach in consolidating Angkor monument. The mechanical characteristics of "*stacked lime mixed soil*" develops with time, which depends upon how much carbon dioxide could be available from air to make a bridge of lime between soil particles. We may have to wait to know the results of this new material in Angkor.

Laterite is an important material of construction in Angkor monuments and is found major factor of structural failure of the monuments. However, little is known how to prevent decay of laterite. If we have to use laterite blocks as in the Khmer engineer have had done, the structures like Prasat Suor Prat or Library is rather easy to repair, because of its independence. Other complicate structures like Bayon or Angkor Wat, it may be practically impossible to repair or to replace new laterite blocks that were used as foundation or structural elements. We have to make study other alternative methods to support the upper structures by other means for the time being before the complete failure takes place.

10.8 Conclusions

In this chapter, several suggestions are made from viewpoints of geotechnical engineering. Two causes had been identified in the report of Tokyo conference in 1993 that results in structural failure. These are structural design of high masonry upon compacted soil ground and effects of the expansion/contraction of the subsoil. The fundamental mechanical characteristics have been studied in this paper and strong wind and water environments are suggested as additional factors to control the failure.

Needs of further studies are also mentioned on characteristics of compacted fill, slacked lime mixed soil, laterite blocks. Intensive monitoring system is recommended to obtain daily change of response of structures rather than seasonal or annual changes to understand the process of failure through the measured real data. Application of the method of Anastolosis was failed in restoration work of soil and laterite structures in Angkor. It is recommended to make further study of high steep mound of compacted fill and the decay of laterite blocks in terms of Anastolosis.

Leaning Tower of Prasat Suor Prat
Awaiting for Help

11 Conclusions

In this chapter, the author wants to summarize the conclusions of each chapter from chapter 2 to chapter 10.

11.1 Review of historical review of safeguarding Angkor

After French began their efforts of clearance and emergency consolidation in early 1900', they introduced "Anastolosis" from Dutch's work *Borobudor* in Indonesia in 1930'. In 1960, French opened Angkor Conservation Office and continued the efforts of safeguarding the monuments until the invasion of Pol Pot into Angkor area in 1970. There was a break of the safeguarding activity from 1970 to 1993, when the UNESCO took the initiative to coordinate the international activities for safeguarding Angkor and had an international conference in 1993 in Tokyo. Since them, several organizations from different countries including JSA have been working on safeguarding Angkor.

11.2 Review of conservation method for Angkor monuments in the past

"*Anastolosis*" is the way to be followed during conservation of cultural heritage. Anastolosis insists to use "original material" by "original method," if otherwise the heritage fails.

If we follow "*Anastolosis*" in handling soils and ground, we shall have some difficulties. The high embankment of about 40m with steep angle of slope of 40 degrees at Baphuon temple is a good example how the ancient Khmer engineer knew some method which resulted in success of Baphuon, which our modern geotechnical engineer do not understand, or could not even estimate. We have to make efforts to study how the Khmer people had handled soils and foundations in the process of construction of Angkor.

11.3 Meteorological and water environmental condition in Angkor area

The Angkor area is covered within Asian monsoon climate zone. The average annual rainfall is about 1400mm with distinct difference of dry and rainy seasons. Rainy season starts from May and ends in October with averaged monthly rain of 200mm/month. Dry season starts from November and ends in April with averaged monthly rain of 50mm/month.

Temperature ranges from 16 to 39°C in a year. It reaches at the maximum around 38-39°C in April when river dries and plants seem almost dead. The best season in a year is from December to February when the temperature becomes mild under dry season.

Strong wind blows with heavy rain and it is one of the main cause to result in the failure of masonry structures in Angkor.

11.4 Topological and geological setting

The Angkor locates in the middle height of about 25m from sea level on a gentle slope between Tonle Sap in the South and Mt.Kulen in the North. Mt.Kulen, 25km north of Angkor site, is believed to have provided sandstone material of the monuments.

Five deep borings in the Angkor area have shown that the base rock exist about 80m from the ground surface. The top surface of about 40m is silty sand soils of brown to yellow in color. The standard penetration test resulted in increasing SPT blows from 5 at the surface to 30-40 in the deeper layers.

The top surface has strong effects of seasonal change, which makes SPT=20 of very hard ground in dry season and decrease about 5 in rainy condition. This is caused by change of underground water level. The monitored results of seasonal changes of underground water level showed that water level becomes very high to nearly surface during rainy season, however, it drops down to 4-5m from the surface.

Underground water in Angkor area is pumped up and used by people in the region. More than one thousands of pumps in Siem Reap city were surveyed and it turned out that the depth of the well has become deepened recently from 10m to more than 30m from the surface, which means water level is lowering.

If this trend continues the water in the ground shall be dried up in the near future and the ground settlement shall be accompanied. The settlement shall cause the differential settlement of the monument in Angkor. To avoid settlement of the ground, it is necessary to control pumping water in the area.

11.5 Geotechnical characteristics of Angkor Region

Samples from boring were tested and the results are as follows,

1. The top surface soil of 40m in the area is lateritic soil of silty fine sand and yellow to brown in color.
2. The main components of mineral are quart and kaolinite.
3. Natural water contents ranges from 10 to 20 % with pH=6 in average.
4. Top surface soil of 5m has strong effects on seasonal changes of weather.

Geotechnical conditions in Angkor region is reviewed and the following conclusions are obtained.

1. Top surface of about 40m in thickness is found lateritic soil as a common ground in the area based upon several geotechnical boring as described in the preceding chapter.
2. Ground consists of silty sand with alternation of sandy rich and clayey rich portions.
3. SPT values increases with depth from N=5-10 at the surface to N=50 at 40m in depth. The upper surface ground of 5-6m becomes weak in rainy season and hardens in dry season.
4. Ground water changes its level about 5-6m between rainy and dry season.
5. The upper surface ground of 5-6m may not be reliable as a foundation of structures due to the effects of under ground fluctuation.

11.6 Stability of Tower of Prasat Suor Prat

Stability of Prasat Suor Prat was discussed based upon observation of present structure. These Towers are independent squired structure of 10m x 10m in width and about 15m in height. Towers near South and North Ponds are found inclined into ponds. The north embankment of South Pond has been displaced at the S1 Tower due to the load of the Tower. The ground behind the embankment where displace into pond was also displaced into the pond being expanded. The expansion of the ground

induced widening of the foundation of Tower near the Ponds.
N1 Tower is found at the most critical state against collapse in terms of the present inclination and N1 Tower was discussed in detail.

The mode of deformation was studied by leveling the stone surface and measurements of dimensions of basic length of the structure. Based upon differential height of the foundation along the peripheral of the Tower, w found the foundation of Tower N1 inclined to northwestwards with 0.4m/10m.

There are four walls, each of which has opening in squired shape of about 2m in length. The horizontal beam element of sandstone at the bottom of opening is found collapsed. The collapse was caused by complex mechanism including bending and shear failure caused by overstressing of foundation laterite block beneath the horizontal beam.

The bottom lengths of the openings are longer than the top one with about 10cm.
The foundation of the structure is made of masonry laterite blocks. The horizontal openings between adjacent blocks are measured. The sum of opening for each wall corresponds well to the difference of top and bottom length of opening in walls. It is concluded that the foundation has been spreading out horizontally that makes wider bottom dimension than upper one.
A fresh crack was found on a surface of a laterite block, which may indicate the continuation of the horizontal spreading. The present structure is not stable and the movement of spreading and inclination may be continued in the future.

The monitoring of behavior of Prasat Sour Prat as well as ground movement and suction pressures were performed. The settlement during dry season and swelling in rainy season are confirmed by seasonal changes of underground water and suction pressure. If the level of underground water is lowered by 10m, the settlement is anticipated as nearly 20mm, which may be critical to masonry structures.

It gave a suggestive result that we did have had a chance to observe the long-term creeping phenomena of inclination of the Tower N1, Prasat Suor Prat after the heavy rain in September 1997.

11.7 Stability of Main Tower at Bayon and some results based upon monitored stone block behavior

Stability of the Central Tower of Bayon is quite different from what is considered for Pisa tower in Italy because of the aspect ratio. It is apparent to see the lack of the symmetry of the Tower. The major reason of the non-symmetry of the Tower might be falling out of the outer surface stones one by one in progressive manner.
Based upon visual observation, we found the several facts that might be related with instability of main tower.

1. Fall off of stone element from central tower.
2. Different height of the base level of the tower foundation on the upper terrace
3. Damage of Bridge between central and sub-towers.
4. Vertical opening of the stone columns of central tower
5. Cracks on the stone surface that may be tension failure caused by horizontal movement and/or lean out of the stone columns.

6. Rooting between the stones has caused vertical opening of stone columns. Small size sand and gravel tumbled in the gap between the stones also have caused to widen the opening.
7. Heavy chemical weathering on the surface on the stone were identified.

The process of falling off the outer stone is estimated as follows,

1. Lean-out of the masonry column by some reason
2. Horizontal displacement of the pillar initiates tension failure in the bottom stone beneath the pillar.
3. Progress of tension cracks finally causes failure of the bottom stone.
4. The bottom fails, which may results in whole column above the stone fall-out from the Tower.

Monitoring of open/close of gap between stone blocks revealed that the strong wind has resulted in non-reversal type movement, which may cause lean-out horizontal displacement of the masonry column.
Based upon monitoring of gap sensors and inclinometers, we observed some behavior of the tower and obtained conclusions as follows,

1. Gap between stones opens at night and closes in daytime, due to the change of the temperature.
2. Sudden large gap changes have been observed when the strong wind blows with greater than 5m/sec. The wind action may induce to accelerate the vertical opening between the stone columns.
3. Change of inclination of central tower was observed within a few mm/m in the last ten months. Since the monitoring has interrupted for some duration, the observation is to be continued.

Further necessary works are as follows,
Geotechnical condition under main tower of Bayon is to be studied.
The reason for the different height of the foundation level of the main tower at upper terrace is to be examined.
Since the fall-out of stones from the central tower is one of major process of structural failure, some possible countermeasures should be considered and compared theoretically and through experimentally.
Displacement between the central and sub-tower is to be observed to evaluate the structural stability and to consider countermeasures to consolidate bridge beam portion of the tower.
The weathering process of the stones of the tower and evaluation of the decaying is necessary to prevent or postpone the weakening the stones.

11.8 Restoration work of North Library at Bayon Temple, Angkor Thom

In the restoration work of the North Library at Bayon, geotechnical engineering was one of major disciplines to be considered. One of the problems was how to keep authenticity as ancient Khmer culture.
Based upon the slope failure experience, French team had to introduce a hidden retaining wall of

reinforced concrete inside the fill at *Bapuhon*. They extended this design concept to restoration work to Terrace of King Leper.

The height of the platform made of soil North Library is about 5m, which is the same height where French team experienced failure at *Bapuhon*. JSA adopted another way of increasing soil characteristics by mixing slacked lime.

The development of strength of slacked lime mixed soil is slow compared with cement mixed one. One of the disadvantages of slacked lime mixed soil is to take longer period to confirm the required mechanical characteristics.

The curing effect was confirmed by testing at various aged period of cores that were sampled at the initial stage of filing platform.

So far, the results of soil mixed with slacked lime were satisfactory. However, it should be observed with care in the future of long period under severe climate conditions.

11.9 Laterite as a construction material in Angkor

In this chapter, the author explained the basic characteristics of laterite, which was one of the basic construction materials in the construction Angkor monuments.

The laterite is a product of chemical weathering of rock under tropical conditions. Chemical process in the tropical region is to accumulation of higher contents of iron oxide and Aluminum oxide in the upper surface of ground. Iron oxide and Aluminum oxide works as strong bond among sands and gravels.

The laterite blocks were used as structural member covered by sandstone block with relieves on its surface. However, Several examples of structural failure resulted by weathering of laterite were shown in the chapter.

The inclination of structures at shoreline towards water was caused by decay of laterite blocks.

The P-wave velocity was measured for three groups of laterite classified by masonry expert. The velocities correspond well with each group and may be used to check the laterite blocks for use.

The author thinks the decay of the laterite had resulted in one of the major causes of structural failure of Angkor monuments.

11.10 Suggestions on safeguarding Angkor monuments

In this chapter, several suggestions are made from viewpoints of geotechnical engineering. Two causes of geotechnical engineering had been identified in the report of Tokyo conference in 1993 that results in structural failure. These are structural design of high masonry upon compacted soil ground and effects of the expansion/contraction of the subsoil. The fundamental mechanical characteristics have been studied in this paper and strong wind and water environments are suggested as additional factors to control the failure.

The impending danger of the embankment of the Angkor Wat was referred. The piping of the embankment and the resulted void in the embankment should be studied and repaired immediately to avoid the collapse of the embankment near the west causeway of the Angkor Wat.

Needs of further studies are also mentioned on the ancient method of compacting fill, design method of slacked lime mixed soil, decay characteristics of laterite blocks.

Intensive monitoring system is recommended to obtain daily change of response of structures rather than seasonal or annual changes to understand the process of failure through the measured real data. Application of the method of Anastolosis was failed in restoration work of soil and laterite structures in Angkor. It is recommended to make further study of high steep mound of compacted fill and the decay of laterite blocks in terms of Anastolosis.

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We were very successful to conclude the stability based upon the analysis of the measured data of inclinometer along several boreholes in the slope during excavation. This was my first experience to apply geotechnical discipline to preserve historical monuments.

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