KGS Fall '95 National Conference
28, October, 1995/Seoul/Korea

A Glimpse of Some Earthworks and Foundations in Ancient China

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ABSTRACT: Some of the ancient earthworks and foundations in China such as the Great Wall and Tu-jian-yan Irrigation Head Works as well as the foundations of several ancient bridges and pagodas are introduced in the paper with emphasis on their geotechnical engineering aspects.

1. INTRODUCTION

China is an old nation having a long history of several thousand years. The invention of papermaking, compass, gunpower and the art of printing, known worldwide as the four great achievements of the ancient China, contributed much to the progress of the human society.

In the area of civil engineering, despite of the fact that the science of soil mechanics and foundation engineering has come into existence for but one hundred years or so, it is undoubted that people all over the world had built houses, bridges, earth dams and different kinds of structures on soil foundations and made use of soils as construction material long long time ago. By exploring some of the ancient earthworks and foundations in China, we can realize from one aspect how our ancestors had successfully and creatively solved various kinds of geotechnical problems by giving full play to their ingenuity and imagination on basis of their vast experience in life and production.

2. THE BAN-PO SITE

In 1954, in the outskirt of Xian city located in the middle reach of the Yellow River (Fig.1) which is the birthplace of China's ancient culture, a great number of cultural remains were unearthed by archaeologists and living conditions of Banpo people who lived there some 6,000 years ago belonging to the Neolithic Age were revealed. This splendid archaeological achievement attracted world interest and the Chinese government decided to set up a museum on the spot to protect the ruins at its original state and open it to the public.

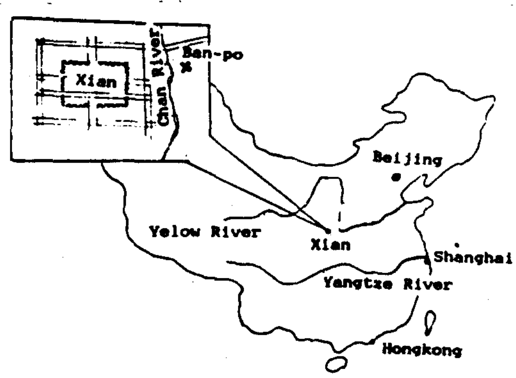

Fig.1 Location of Ban-po Site

Seen in Fig.2 are some of the stone tools unearthed--axe, chisel and hoe. They were not simply chipped, but carefully polished and even amazingly drilled. Among the earthen articles such as basin, bowl and jar as shown in Fig.3, there is an earthen bottle with pointed bottom (Fig.4), which was used apparently by the Banpo people to pick up water from the river. It vividly displays the intelligence of our ancestors. The bottle stands upright when the rope attached to it is lifted (Fig.5). Once the rope is loosened, the bottle tilts automatically and gets in water. When the bottle is full, it automatically resumes upright position and can easily be lifted. It is amazing that the law of center of gravity was so well applied by the Banpo people some 6,000 years ago to create such an extraordinary bottle for the ease of lifting water.

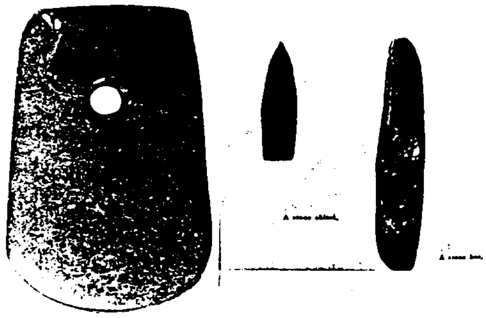

Fig.2 Stone tools

Fig.3 Earthen articles

Fig.4 Earthen bottle with pointed bottom

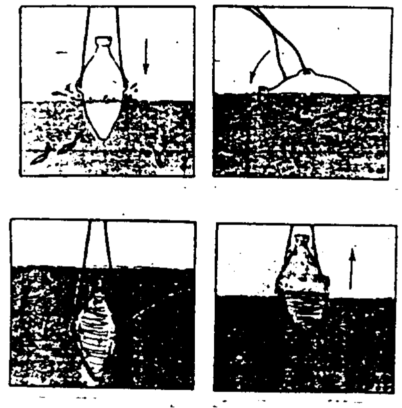

Fig.5 Working principle of bottle with pointed bottom

Some of the ruins of houses are seen in Fig.6 and Fig.7. The one in Fig.6 must be a square-shape semi-underground house characterized by its sunk floor and the pit-walls serving as house-walls.

Fig.6 Ruins of a square-shape semi-underground house

On the other hand, the one seen in Fig.7 must be a round-shaped house at ground level.

Fig.7 Ruins of a round-shape house at ground level

What attracted geotechnical engineers most is the discovery of a number of holes for posts with surrounding clay post-holders in the ruins of many houses (Fig.8). Wooden posts once rested in the holes were rotten and the signs of ramming with pebbles and pieces of broken earthware can be seen at the bottom of holes. The surrounding post-holders were clay rammed in layers (Fig.9). This is undoubtedly the trace of the earliest column foundations ever discovered.

Fig.8 Holes for posts with surrounding post-holders

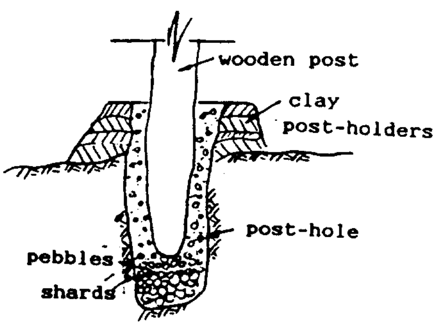

Fig.9 Sketch showing the earliest column foundation

At the periphery of the Banpo village, large and deep ditches could be seen (Fig.10). They seem to be defense ditches to protect the villagers from the attack of beasts and outsiders. The ditch measures 6-8m wide at top and 1-3m at bottom with 5-6m in depth and more than 300m in total length. It is astonishing that such a giant earth excavation job estimated to be in the amount of more than 10,000 cubic meters was completed in the Stone Age.

Fig.10 Large and deep ditches surrounding the Ban-po village

3. COMPACTION AND SOIL FOUNDATIONS

Use of earth as building material and as foundation as well as the technique of compaction associated with it dates back to the early history of mankind. For example, the remnants of a city wall belonging to the Neolithic Age about 4,500 years ago was unearthed in 1983 in Henan province. On the wall remnants, traces of compaction in layers can be clearly seen.

Rammers used in different ages are shown in Fig.11. (a) is the stone rammer unearthed in Inner Mongolia from ruins belonging to the Neolithic Age while (b) is the stone rammer unearthed in Shanxi province, belonging to Qing dynasty about 2,000 years ago. It is of sanstone, having a pit on top for fixing a wooden handle and a pin slot on two sides. An iron rammer shaped like a ball belonging to Song dynasty about 1,000 years ago is shown in (c). Many more kinds of rammers came into use in the later dynasties, including wooden tampers like those shown in (d) and (e).
Shown in Fig.11(f) is a kind of heavy rammer used for large area compaction such as earth embankment and high pedestals. It may be of stone or iron, with 30-40cm in diameter and weighs about 60-100 kilograms.
The rammer is usually operated by a team of 8-12 persons, each holding one of the ropes fastened at each hole on the rammer. The rammer is thrown and raised to the top of its travel by pulling the ropes at the combined effort of the team and let falling down freely to pound the earth surface.

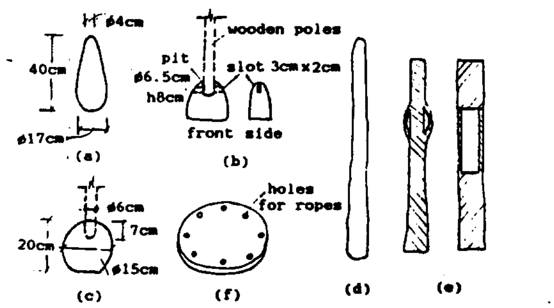

Fig.11 Rammers used in different ages

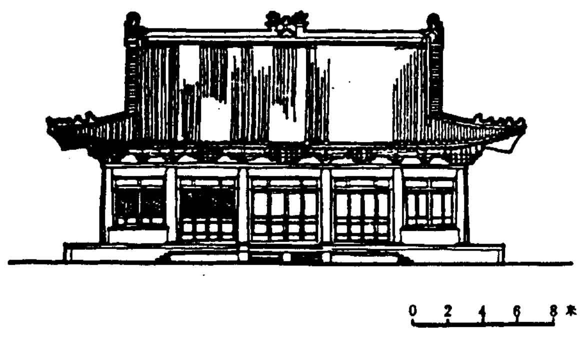

Fig.13 Typical front view of a Chinese hall, temple or palace

Some other types of heavy rammers are shown in Fig.12. These heavy rammers were used not only for compaction but also as pile drivers in the olden days.

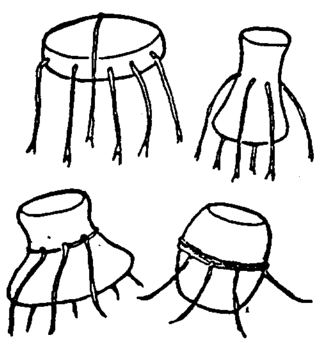

Fig.12 Heavy hand rammers

Fig.13 shows the typical front view of an ancient Chinese hall, temple or palace. It consists of three portions: a wide and high base at the bottom known as "high pedestal", the wall and column structure in the middle and a lofty roof on top.
The high pedestal (Fig.14) is an earth-fill enclosed by stone or large bricks. Its height is usually 1/4 or 1/5 to that of the columns, and extends beyond the outer columns by 3/4 or 4/5 to that of the roof. It is carefully compacted and founded either on natural ground or on compacted lime-soil depending on the soil condition.

The typical foundation set-up for wooden column is shown in Fig.15.

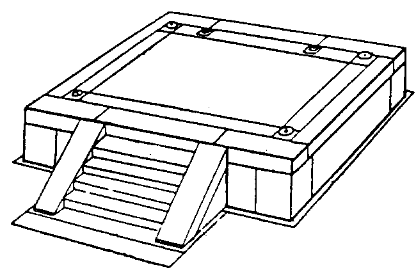

Fig.14 The "high pedestal"

The column rests on a stone cap on top of a brick or stone pier which rests on a compacted lime-soil cushion, thickness of which varies from 30 or 40cm to more than a meter depending on the column load and the soil condition.

The typical construction procedure is as follows. Complete all the column foundations first, and then construct low walls in-between the brick piers forming many rectangular pits into which soils are filled and compacted. Finally, finish the surface of the high pedestal with brick paving.
Use of lime as mortar dates back to the early ages, but the use of lime to be mixed with clayey soil in certain proportion (usually 3:7 or 4:6 in volume) and be compacted to form lime-soil foundation to support loads did not come into practice in China until Ming dynasty about 500 years ago. Prior to that, alternate layers of plain soil and other materials such as debris, pebbles and iron bits were commonly used to improve

the bearing capacity of the natural soils, examples of which are shown in Fig.16.

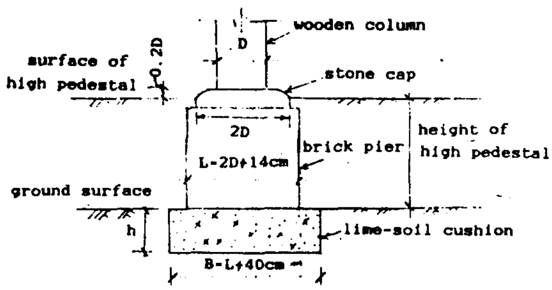

Fig.15 Typical foundation set-up for a wooden column

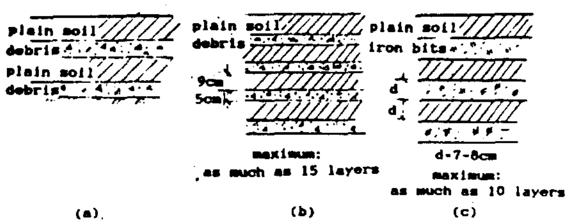

Fig.16 Foundation improvement

Fig.16(a) is the profile of the foundation soil for a pavilion of Song dynasty; (b) is that for columns of a famous palace in Shanxi province built in Yuan dynasty. Number of layers differs, depending on the column load. One attains as much as 15 layers; (c) consists of alternate layers of loess and iron bits, 6-10 relatively thin layers of 7-8cm in thickness.

Since Ming dynasty, lime-soil foundations has come into use extensively in all parts of china, including nowadays.

4. WALLS AND THE GREAT WALL

Walls for dwelling houses in China, prior to Ming dynasty, were mainly of earth. Earth is readily available and easy to handle. Earth walls are fire-proof, good for heat insulation and can keep out the cold.

There are two kinds of earth walls, one is that of tamped earth and the other is that of sun-dried mud bricks.
The tamped earth walls are constructed as follows (Fig.17 and Fig.18,a): wooden rods and poles are bound together and erected as scaffold to hold the climbing shuttering (boards or rafters) raised lift upon lift till the wall has reached its full height, and then moist earth are filled and tamped within. On remnants of ancient tamped earth walls, holes left where rods once passed through can be seen, usually 6-10cm in diameter at 1-1.5m horizontal distance and 0.8-1.0m vertical distance.
Lifts, usually 8-12cm in thickness, and tamper prints of different diameters are also detectable on ancient earth walls in many instances.

Fig.17 Construction of tamped earth wall

The disadvantage of tamped earth walls is that it takes months for the wall to get dried thoroughly and be capable of weight-bearing. If earth are made into adobe (sun-dried mud bricks) first and then use them to built walls, mud bricks can be prepared in the dry season, easily sun-dried and stored for use.

The technique of making sun-dried mud bricks and using them to build walls dates back to Zhou dynasty(800 B.C.). The dimension of mud bricks at that time, according to unearthed evidence, was in the order of 47x17x7.5cm. Mud bricks are still widely used nowadays in the rural area of China for low houses. And strange to say, the process of making mud bricks remains almost unchanged in the past 2,700 years.

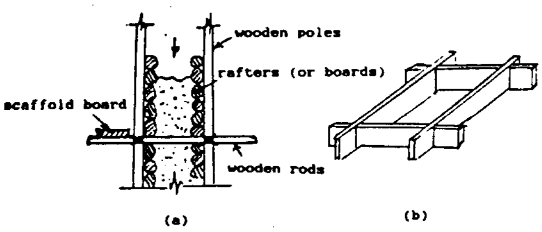

Fig.18 Scafford for tamped earth and mould for mud bricks

Moist earth are filled into the wooden moulds(removable elongated boxes without top and bottom as seen in Fig.18,b) and tamped. Then dismantle the mould, take out the mud brick and pile them up with space in between and sun-dried.

In some cases,straw or grass are added in the course of mixing the earth with water in order to increase the tensile strength of the mud bricks and prevent cracking.

There are three types of adobe wall: (1) exclusively of mud bricks; (2)mud bricks as core with baked bricks as facing; (3) mud bricks erected on top of a tamped earth wall.

To prevent the lower portion of the earth wall from getting damp, earth walls are usually founded on brick or stone strip footings extending 50-60cm above the ground surface with compacted earth or lime-soil cushion underneath (Fig.19).

Earth walls are usually coated with mud and whitewashed occasionally. If unroofed as used for the enclosure of a yard, the top of wall is usually covered with tiles or stone plates to prevent water infiltration.

In Southern China, earth walls are sometimes reinforced with bamboo---two pieces of bamboo stems are placed in-between every two layers of mud bricks.

Earth walls were extensively used to form the framework of ancient Chinese cities. There was no ancient city in China without a surrounding wall. Most of the city walls consisted essentially

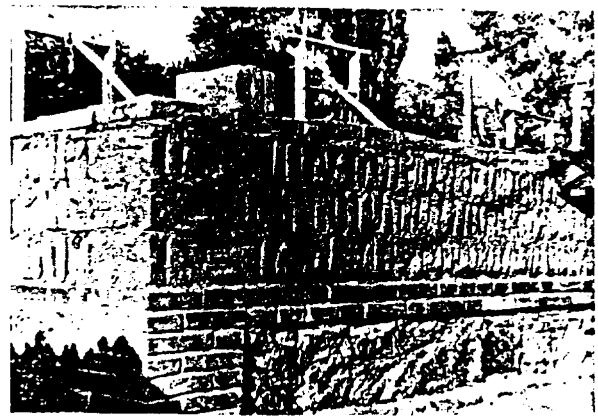

Fig.19 Adobe wall

of successive layers of tamped earth averaging 8-10cm thick, faced with sun-dried mud bricks or in later centuries faced with large grey burnt-bricks laid in lime mortar. Occasionally, where stones were plentiful, city walls were faced with stone blocks.

Among those city walls built since Ming dynasty, the city wall of Xian is one of the most well preserved which is 12m in height and 15m(top) to 18m(bottom) in width. The earth core consisted of tamped loess mixed with rubbles and large baked bricks, 45x23x10cm in size, were faced on both sides. On top of wall, 2-3 layers of burnt bricks were paved on a lime-soil sublayer of 20cm thick (Fig.20).

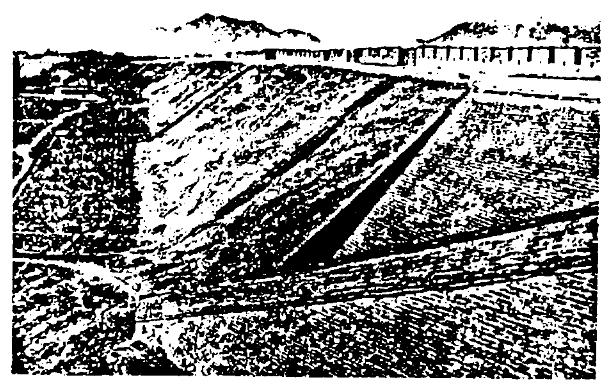

Fig.20 View showing the city wall of Xian

In the inner side of the wall, there were brick drainage ditches(at 60m interval) and ramps (6m wide) giving access to the ramparts at every gate-tower.

The entire wall formed as an integrated fortification system for the city of Xian(Fig.21).

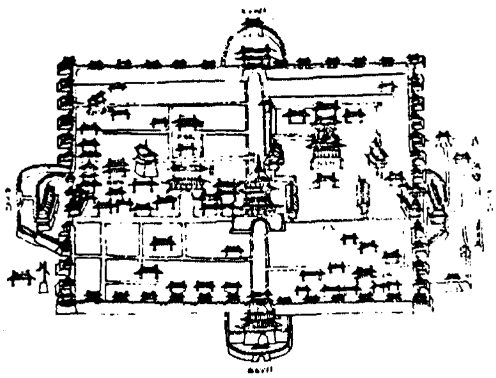

Fig.21 Plan of the city wall of Xian

The Great Wall known as one of the most magnificient structures in the world winds its way across the Northern China, exceeding 70,000km in length(Fig.22). It had been constructed and rebuilt by more than 20 dynasties and feudal principalities, starting in the period of Spring and Autumn dynasty(770-207B.C.) and ending in Ming dynasty (1368-1644 A.D.), taking more 2,000 years.

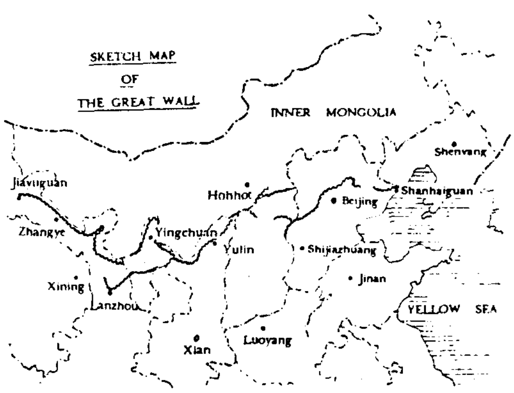

Fig.22 Location of the Great Wall

Seen in Fig.23 and 24 are sections of the Great Wall located in Badaling in the outskirt of Beijing. They were reconstructed in Ming dynasty 350 years ago and renovated in the seventies.
The dimension of the Great Wall differs from place to place as it was built in accordance with the local terrain.
Its maximum width is 5m at top and 7m at bottom and its maximum height is 8m. The materal used also varies from place to place depending on availability.

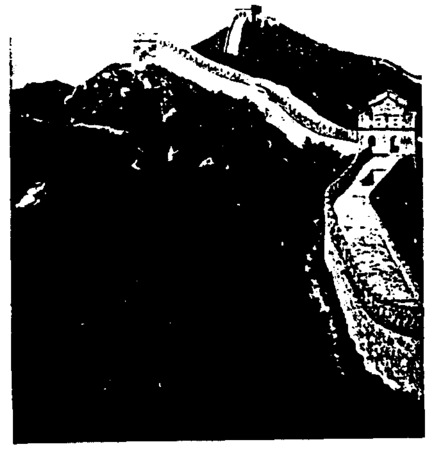

Fig.23 The Great Wall near Badaling

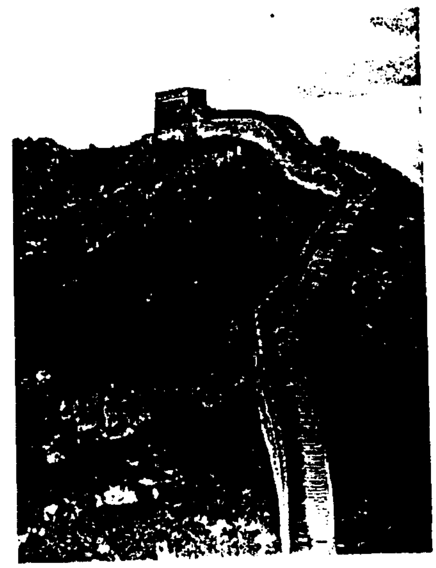

Fig.24 The Great Wall reconstructed in Ming dynasty

Earth, bricks and stones are the three major materials used; if piled 35cm thick, 5m wide, they would encircle the earth 30-40 times.

As seen in Fig.25, some of the early sections of the Great Wall were built of loess. They were well compacted and stood for centuries.

Shown in Fig.26 is one of the many beacon, towers seen along the Great Wall. Its dimension is 16m by 16m and 20m in height. Most of them were tamped earth, some were mud-bricks and some were combination of the two. Holes for erecting scaffold during construction were left on the walls.

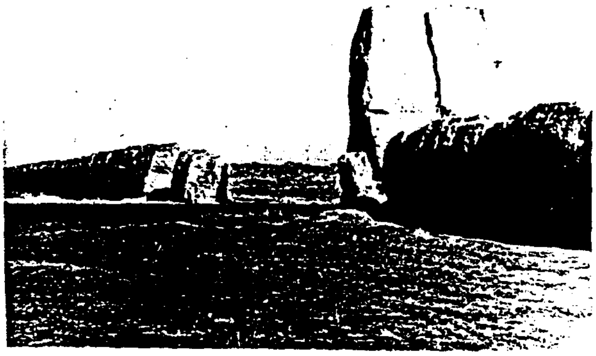

Fig.25 Section of the Great Wall built of loess

Fig.26 Beacon tower

In Gansu province, Northwestern China, sections of loess walls built in Han dynasty(200 B.C.) were found to be reinforced with twigs and reeds as can be seen in Fig.27. Layers of reeds about 6cm in thickness were placed in-between soil layers for every 15cm lift. The placement of reeds not only strengthens the wall but also prevents the alkalization of soil. Reeds were well preserved in the centuries.

The Great Wall constructed or rebuilt in Ming dynasty were most up to standard. Its cross-section, together with that of the watch tower, is shown in Fig.28. The stone base often consists of large granite blocks and

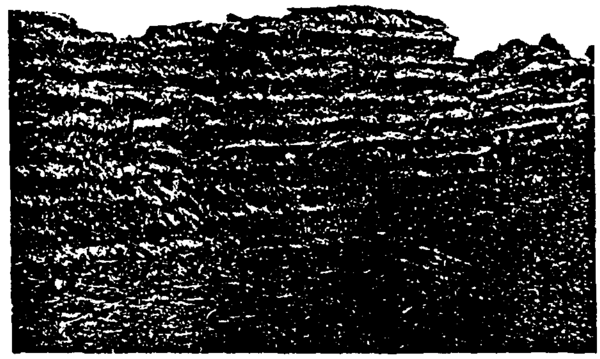

Fig.27 Loess wall reinforced with twigs and reeds

the facings for earth cores are either of stone or large burnt bricks laid in mortar (Fig.29). The top of wall is usually paved with 3 or 4 layers of bricks, 4-5m wide, accommodating 5 horses or 10 persons abreast. There is a 2m high battlement on the outer side, which contains openings on top to watch and from which arrows can be discharged. On the inner side, there is usually a parapet wall, 1m high, with openings at bottom for drainage at certain distances (Fig.30).

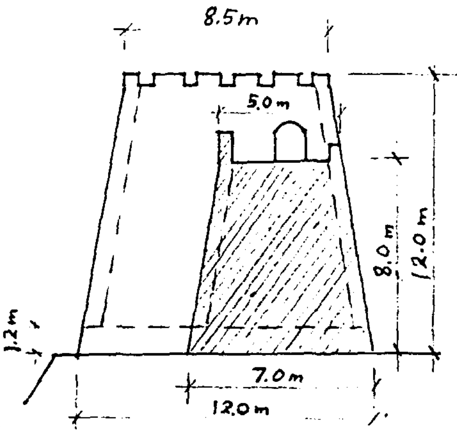

Fig.28 Cross-section of the Great Wall and watch tower

Evidence reveals that in the construction of the Great Wall in Ming dynasty, rice juice had been used to strengthen the lime-soil foundation for some of the wall sections. It has been proved that by sprinkling rice juice at each lift and allowing the rice juice to infiltrate into the lime-soil, the water resistivity and solidness of the lime-soil can be improved.

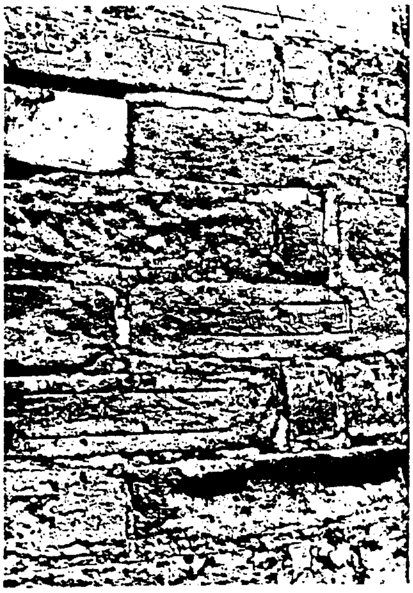

Fig.29 Burnt bricks laid in mortar as facing for earth cores

Fig.30 Top of the Great Wall

There is evidence that this unique technique of applying rice juice to strengthen lime-soil had also been used in ancient China for the foundation treatment of important structures such as the palace and mausoleum of the emperors.

It may be said that the Great Wall is the most magnificient achievement which best illustrates the hard-working spirit and wisdom of the Chinese people. "To suit local conditions and use locally available materials" was the principle adopted. To avoid costly transport of materials over long distance, earth and stone were used whenever available. Bricks were burnt by setting up kilns nearby.

The difficulty involved in the construction work was tremendous, considering that there were so many mountain ridges and gullies, deserts and pastureland over which work were to be carried out without the aid of machines and modern transportation. Long stone slabs (some were 3m long) weighing more than one ton were used in the Juyongguan section along very steep mountain ridges. One can imagine the vast difficulty in transporting enormous quantity of such stones and bricks as well as earth and limes up the mountains.
According to records and legends, three kinds of methods were used for transporting building materials: (1) by manual labor--carried on back of man, or men stood in a line to pass the material from hand to hand; (2) by simple mechanical means such as handcarts, rolling logs and simple cable-ways. Windlasses were installed on top of ridges to hoist huge stones from below step by step; (3) by animals like sheep and donkeys which are good mountain climbers. We may say that every brick, every piece of earth and every stone had been built with the labor of the people. The massive construction project represents the ingenuity, wisdom and perseverance of the Chinese people in conquering difficulties.

5. TU-JIAN-YAN IRRIGATION HEAD WORKS

Chinese people have been outstanding among the nations of the world in their control and use of water. Protection from flood and construction of irrigation systems for wet rice agriculture are the two main hydraulic problems faced by the Chinese people throughout the centuries.

To prevent flooding, people living along the Yellow River and Yangtze River unceasingly built dikes and levees for no less than 2,000 years. The famous Jin-jiang Great Dike along Yangtze River near Wuhan was first constructed in 405 A.D., height of which attained 15m after being continuously reconstructed for generations.

Construction of earth dams to retain water for irrigation also started early in Zhou dynasty. Record reveals that an earth dam was built in Shou-hsien, Anhui province, in 590 B.C. to form a reservoir for irrigation. This is the

earliest earth dam mentioned in the local chronicles of China. The thing to be regretted is that nothing was on record about its size or height.
In 514A.D., an earth dam called Fu-shan-yan was built in the middle reach of Huai River, height of which attained 18m which was rather high at that early date.

Most of the earth dams built in ancient time were of homogeneous clayeys soils compacted in layers using heavy hand rammers as those shown in Fig.12. However, in Northwestern China where loess were predominant, some of the small earth dams had been constructed by means of sluicing similar to what we do with hydraulic fill dams today.

The oldest irrigation work in the world may date back as early as 40 centuries B.C. in the basin of Nile River. In countries like India and Peru, the construction of irrigation works also started very early. The history of irrigation and water conservancy in China extends for thousands of years and some of the ancient irrigation works were really outstanding even if judged from the standpoint of modern engineering.

For example, the world famous Tu-Jian-Yan Irrigation Works located in Si-chuan province (Fig.31) was built 2,200 years ago and is still in use. It was designed and built under the supervision of Li-Ping, known as the father of the Chinese hydraulic engineering.

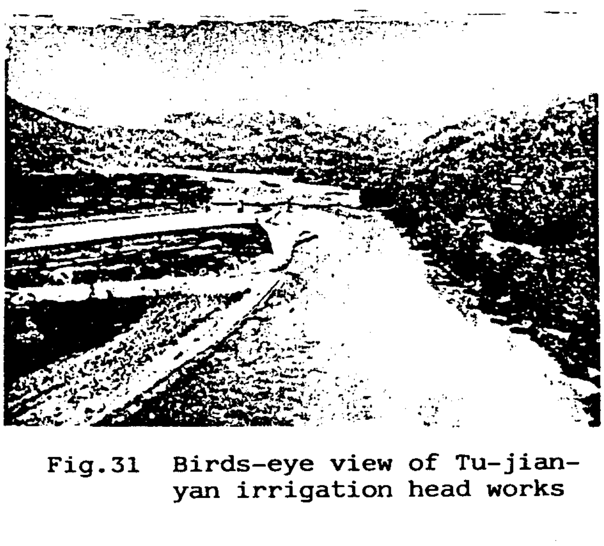

Fig.31 Birds-eye view of Tu-jian-yan irrigation head works

The layout of the head works of Tu-Jian-Yan is shown in Fig.32. At the town of Guan-xian, Ming-jian river making a large turn flows into the basin of Si-chuan from its source in the northwestern hills of the province. Li-ping decided to divide the river at this place by means of a divison-head made of piled stones constructed on an islet in the river, known as the Fish Snout, into an inner feeder canal for irrigation and an outer channel for navigation and flood passage. The location of Fish Snout was so well chosen that in dry seasons the diversion ratio was 0.6,that is, 60% of the river flow would go into the Inner Feeder Canal while in flood seasons the diversion ratio became 0.4.

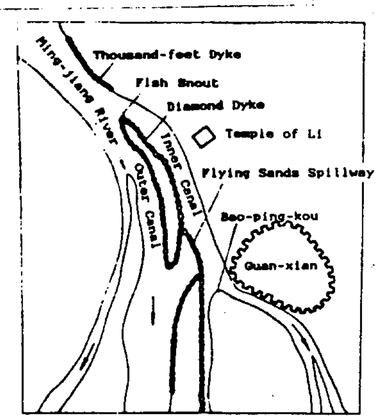

Fig.32 Layout of Tu-jian-yan head works

A large rock cut, 20m wide, 40m high and 200m long, was effected at Bao-Ping-Kou to draw water from the inner feeder canal into the irrigation network. It can be imagined how difficult it was to accomplish such a giant job with no dynamite at that time. It is said that when sound rocks were encountered, workers would first heat them by burning woods underneath and then pour vinegar or cold water on top of them so as to create cracks on rocks for ease of excavation.

From Fish-Snout to Bao-Ping-Kou, the two channels were separated by the Diamond Dyke and the Flying Sands Spillway.
The top of the Diamond Dyke was made higher than the flood level of Ming-jiang river while that of the Flying Sands Spillway was adjusted to the elevation required for flood regulation. When water in the inner canal rose above this level, they would automatically overflow into the outer canal.

Throughout the centuries, the principle set by Li-Ping to maintain the normal fuction of the irrigation system has been well followed, that is," clear out the sediments in the canal beds and keep the dykes and spillways low." The annual repairs begin every year in mid-October. A row of weighted wooden tripods(Fig.33) is placed across the outer canal at its inlet and covered with bamboo matting plastered with mud to form a temporary cofferdam, thus diverting all the flow into the inner canal.

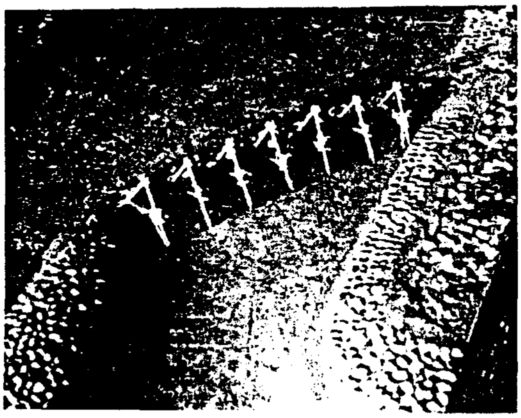

Fig.33 Weighted wooden tripods

The bed of the outer canal is then excavated to a predetermined depth, and any necessary repairs to the division heads are carried out with the aid of gabions (Fig.34).

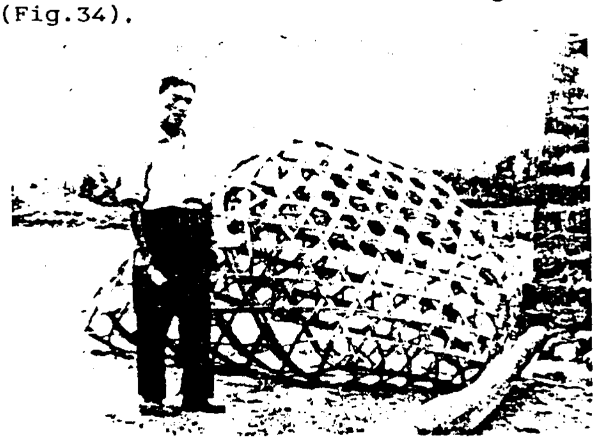

Fig.34 Gabion---bamboo cage to be packed with large stones

About mid-February, the "cofferdam" is removed and re-erected at the intake of the inner canal, so that all water flows to the outer canal, and similar maintenance of the inner system is effected. Seen in Fig.35 is the simple dredging boat used in the olden days.

Usually on the 5th of April, the ceremonial removal of the cofferdam marks the opening of the irrigation season, as from April onwards the flow increases until June and July, reaching a maximum flow of 7,500 cubic meters per second, after which the flow gradually decreases.

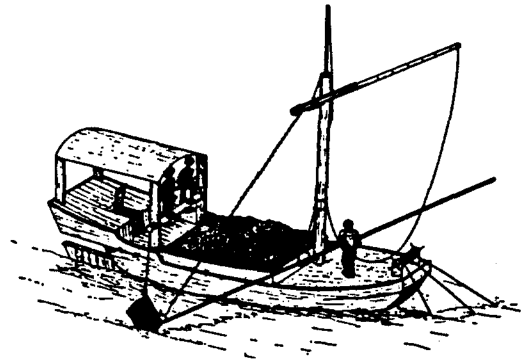

Fig.35 Dredging boat

In hydraulic engineering, the technique of compaction is of vital importance to assure the stability of embankment slopes as well as the technique of surveying and levelling to assure the correct elevation. Seen in Fig.36 is the primitive level used in ancient China, simply a bowl of water and a stick-ruler.

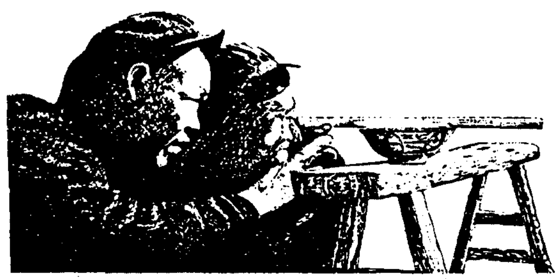

Fig.36 The primitive level

What surprised us most in Tu-jian-yan project is not only the technique of construction but the basic knowledge of hydraulic engineering that Li-Ping and his followers had 2,200 years ago. Their perfect design of an irrigation system was by no means inferior to what we have today.

6. BRIDGE FOUNDATIONS

There are thousands of ancient bridges in China that are still in service. Some of them are magnificient cultural relics.

One of the oldest and well-preserved arch bridges in China is the famous Zhao-zhou(An-Ji) bridge located in Hebei province, built in Sui dynasty about 1,400 years ago (Fig.37).

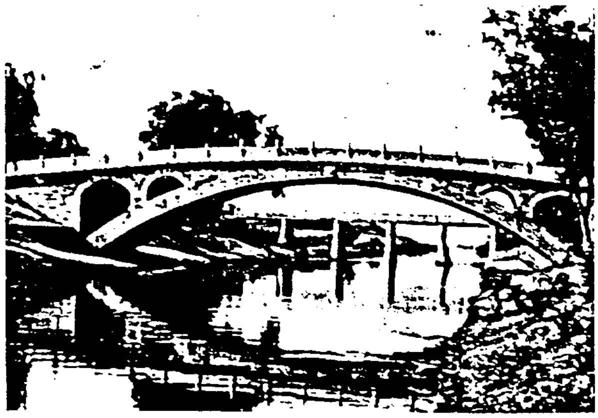

Fig.37 Zhao-zhou(or An-Ji) bridge

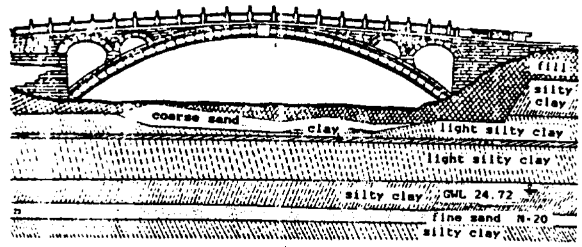

Fig.38 Geological profile

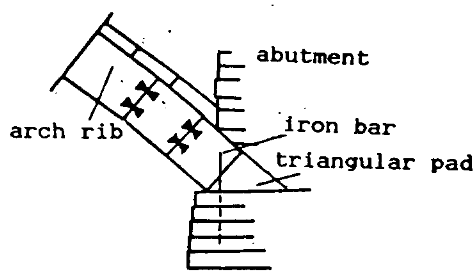

Fig.39 The abutment

It is a single segmental stone arch bridge with 37.02m span, 7,23m rise. The width of bridge is 9m formed by 28 individual arches bounded transversely. Each of its spandrels is perforated by two small arches having spans of 3.8m and 2.85m respectively. This kind of design, believed to be used for the first time in the world, not only makes the bridge so graceful, but also increases the flood discharge capacity and decreases the dead weight of the bridge. The bridge, exquisite in workmanship, unique in structure, well proportioned and graceful in shape, has been regarded as one of the great engineering achievements in China. Great attention and protection has been given to it through successive centuries.

Geological exploration carried out in 1979 revealed that the soil strata at the bridge site are mainly alluvial deposits of silty clay with sand interlayers (Fig.38). The bearing capacity of the silty clay is estimated to be in the order of 340-350kPa.

The abutment embedded 2.1m below the river bed is made up of 5 layers of massive stone blocks as seen in Fig.39. No piles were found underneath. Through calculation, the pressure exerted by the abutment on silty clay is 310kPa at one end and 440kPa at the other. Strange to say, the ancient builders, by experience, were able to make use of the bearing capacity to such an extent.

As to the resistance against horizontal sliding, the ancient builders had apparently considered the earth pressure acting on the lateral sides of the foundation, hence were able to design such a short, yet safe and economical foundation.

It is noteworthy that the bridge had survived 12 large earthquakes in the history. It stood basically unharmed. And as a straight section of the river was chosen for the bridge site, the topographical features of the river bed had not changed much during the long history. Neither severe scouring nor sedimentation occurred nearby the foundation.

Ba-bridge in Shaanxi province is another ancient bridge noteworthy (Fig.40). In contrast to Zhao-zhou bridge, Ba-bridge had been destroyed and rebuilt several times since it was frist built in Han dynasty nearly 2,000 years ago. It was totally reconstructed in Qing dynasty 160 years ago. It was of timber beam and stone column construction, 415.5m in length, consisting of 67 spans with an average span length of 6m. As can be seen from Fig.41, timber girders (30cm diameter) were placed side by side on top of transverse stone beams supported by 6 stone columns in a row, which rested in turn on independent pile foundations composed of 11 cypress piles (15-20cm diameter) driven 4-5m deep into the alluvial clay deposit. Each stone column was made up of 4 co-axial cylindrical stone blocks, 95cm in diameter and 70cm in height (Fig.42). They were stacked up with groove and tongue connection (Fig.43). Rice juice, cow blood and lime were mixed together and used as mortar to strengthen the connection.

Fig.40 Ba bridge

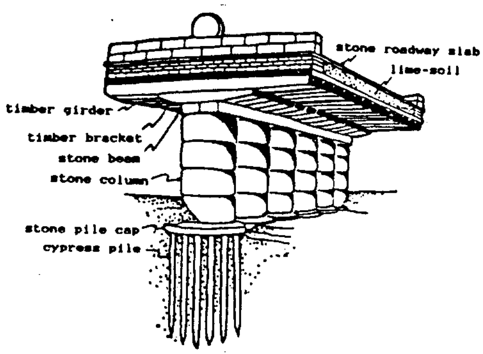

Fig.41 The structure and foundation of Ba Bridge

Fig.42 Stone columns

When the bridge was renovated in 1952, it was found that wooden piles were unrotten, columns were intact and the river protection (lime-soil mixed with rubbles, about 1m thick) was still effective, hence the substructure was used as it was without doing any additional

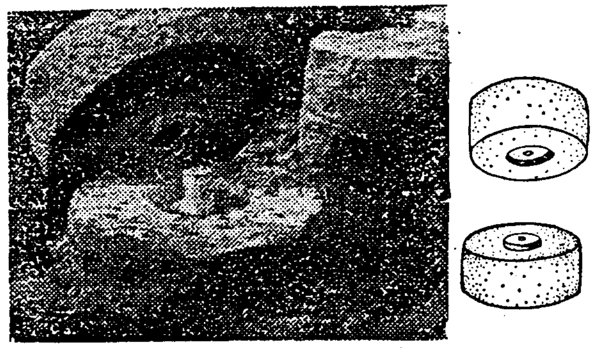

Fig.43 Groove and tongue connection

work. Only the superstruce was reconstructed, changing the wooden girders into reinforced concrete girders to allow passage of motor cars and tractors and widening the width of the deck to set up sidewalks for pedestrians.

It may be concluded that the foundation of Ba-bridge as reconstructed in Qing dynasty proved to be very successful. It had stood not only the heavy load but also the severe trial of flood.

The third example of the ancient bridges to be mentioned is Luo-yang bridge located in Fu-jian province built 900 years ago in Song dynasty (Fig.44). The construction of its foundation is of particular interest.

As the bridge is located at the outlet of Luo-yang river where the stream runs into the East China Sea, the width of river is large, the foundation soil is soft and the water level at the site is subjected to large tidal fluctuation. Consequently, the total length of the bridge amounts to more than one kilometer and special measures had to be taken to construct the foundation.

As the span for stone beams can not be too large, if independent spread foundations were adopted for each stone pier, they would be very close to each other. Hence, instead of adopting independent grillaged spread foundation named "lying-wood foundation" consisting of 2-3 layers of square timber for each pier as usually used for stone bridges in those days, a new kind of "long-raft foundation' was adopted. Rubbles, estimated to be more than 30,000 cubic meters in quantity, were dumped along the longitudinal direction of the bridge, bogged and rammed down to the river bed to form a long continuous raft, 25m in width, more than 500m in length, on which piers made up of long stone blocks of square cross-section arranged criss-cross in layers were founded. Such enormous quantity of rubbles was efficiently dumped from boats simply by swinging the boat laterally as shown in the drawing (Fig.45), which is the practice still in use nowadays in some places in China.

An unique and intelligent method was used to strengthen the dumped rubble foundation. Oysters were purposely bred on the rubbles so as to let the growing shells of the living oysters bind the rubbles together(Fig.46).

Fig.44 Luo-yang bridge

Fig.45 Dumping of rubbles from boats

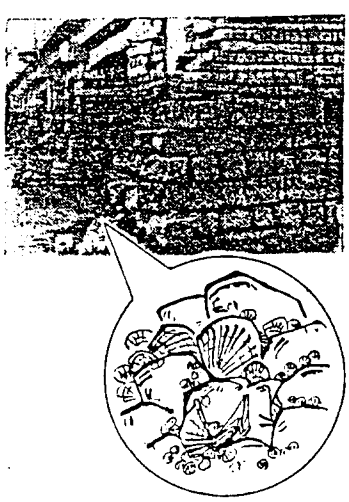

Fig.46 Oysters bred to bind rubbles together

As no further treatment of the deep soil strata had been undertaken, under the action of the heavy dead load, the erosive forces of the strong current and the seismic effect, some of the stone piers are now inclined to a dangerous state.

7. FOUNDATION OF PAGODAS

The pagoda is a great feature of the Chinese landscape. Almost anywhere you go in China, you can see free-standing pagodas of different storeys, with or without external galleries and are some-times square, sometimes polygonal; they may be of wood, more often of brick, rarely of stone and exceptionally of cast iron or bronze. Occasionally they are two or three in a group.

Shown in Fig.47 is the pagoda of Song-ye-si built in the North Wei dynasty (523) in Henan province. It is elegantly polygonal with 12 sides. Its height is 40m. Fei-hong pagoda shown in Fig.48 was built in Ming dynasty (1527) in Shanxi province. It is octagonal, of brick construction with beautiful glazed tile facing, having 13 storeys.

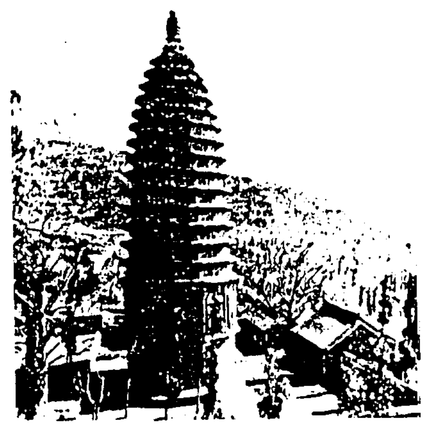

Fig.47 The pagoda of Song-ye-si

The famous twin pagodas of Su-zhou located in Jian-su province can be seen in Fig.49. They were built in Song dynasty (982). Both are of wood, octagonal in shape with 33m in height. The distance between the two pagodas in 19m. Shown in Fig.50 is the Chong-seng-si pagodas built in the 8th century in Yun-nan province, Southern China. Three pagodas are arranged at corners of a triangle in plan. The main one is 58m high with 16 storeys while the two smaller ones are 38m high with 10 storeys. All are of brick.

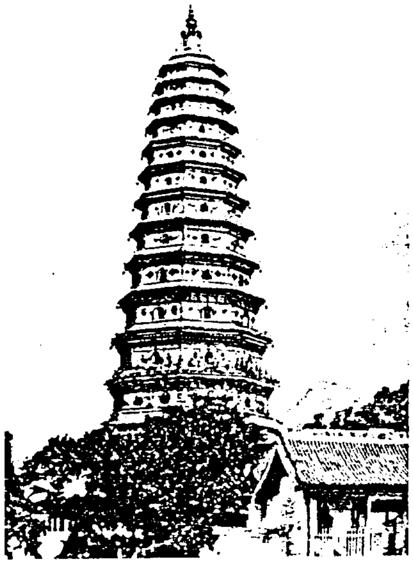

Fig.48 Fei-hong pagoda

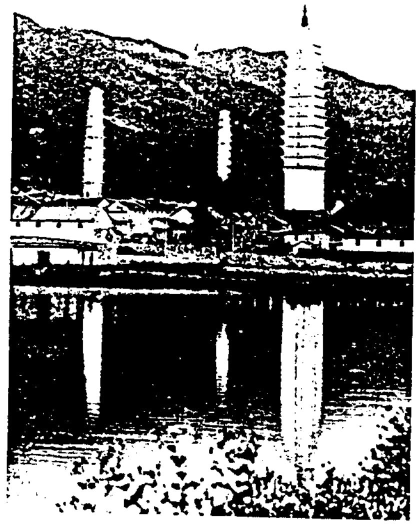

Fig.50 Chong-seng-si pagoda

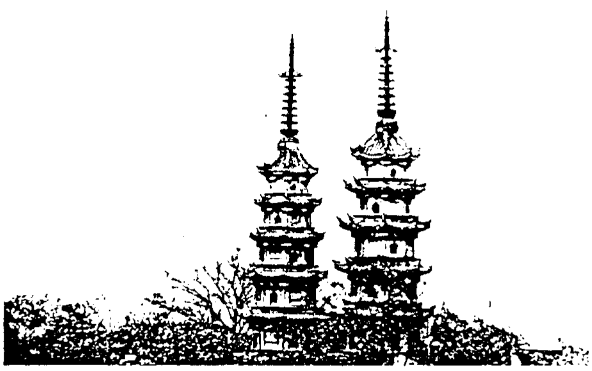

Fig.49 The Twin pagodas of Su-Zhou

Seen in Fig.51 is the largest and tallest wooden structure in the world--Ying-xian pagoda. It was built in the 11th century in Shanxi province, remarkably 67m in height.

Pagodas are of half-foreign origin introduced from Indian Buddhism. They were essentially built as superimposed chapels where Buddhist relics were kept for worship.

Most of the pagodas, being built on solid ground, seldom experience foundation troubles despite of heavy concentrated dead load. However, there were also cases where pagodas inclined due to uneven settlement or piles were used to avoid excessive settlement.

Fig.51 Yin-xiang pagoda

Seen in Fig.52 is the Tiger-hill pagoda located in Su-zhou, Jian-su province. As can be seen in the picture, it inclined to such an extent that it is known as the leaning tower of Pisa in China.

The pagoda was built in the 10th century. It is an octagonal brick structure of 7 storeys with 47.5m in height and 13.66m in base diameter. The weight of the pagoda, totalling 63,000kN, is supported by 12 independent brick footings arranged in plan as shown in Fig.53.

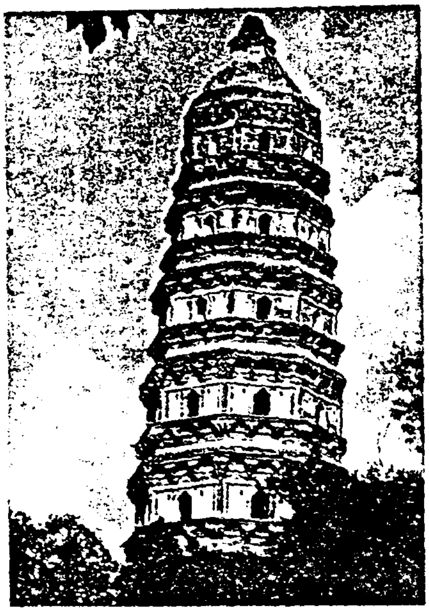

Fig.52 The Tiger-hill pagoda

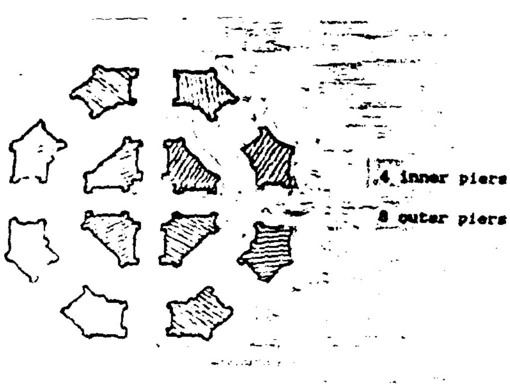

Fig.53 Layout of footings

The pagoda gradually inclined to the NE direction due to uneven settlement through the centuries. Survey conducted in 1957 revealed that the top of pagoda had horizontally moved 1.7m. No measures were taken at that time to halt the settlement and it was decided to repair the superstructure seriously cracked in the course of history. After renovation, however, the weight of pagoda increased nearly 2,000kN. As a result, the inclination was accelerated. In 1978, the horizontal displacement increased to 2.3m which means an average rate of 3cm per year.

The geological profile at the site is as shown in Fig.54. Obviously the uneven settlement is due to the large differenc in the thickness of the soil strata.

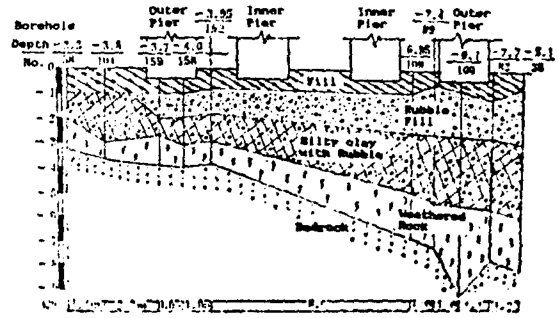

Fig.54 Geological profile

Out of several remedial measures considered, the one shown in Fig.55 was adopted. A total number of 44 shafts, 1.4m in diameter, were dug manually at a distance of 3m away from the outer wall. For every 80cm excavated, reinforced concrete linings of 15cm thick were immediately cast to protect the shaft wall from falling. After reachin 0.5m below the rock surface, reinforcement was placed and concrete poured in each open shaft to form a continuous column wall. Finally, pressure grouting was carried out within the diaphram wall through vertical and horizontal holes drilled at 1.15-1.50m distance and 0.5m deep into the bedrock.

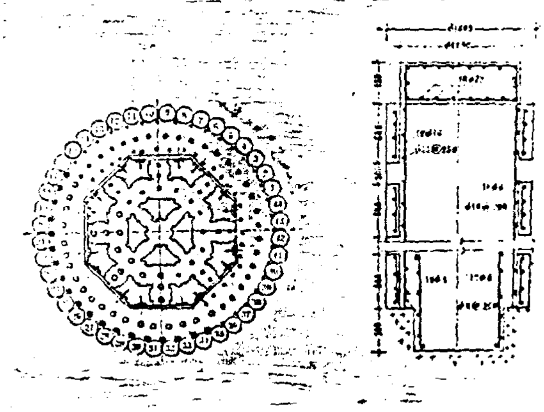

Fig.55 Underpinning scheme

Precise monitoring during and after underpinning indicated that the remedial measures adopted were successful in controlling the uneven settlement and inclination.

Fig.56 shows the Long-hua pagoda in Shanghai. It was built in Song dynasty (977). It is of brick, octagonal, with wooden eaves. Partial excavation conducted in the sixties revealed that the pagoda has pile foundation as shown in Fig.57.

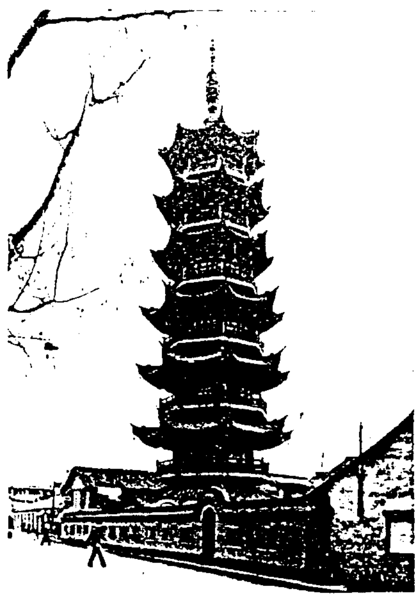

Fig.56 Long-hua pagoda

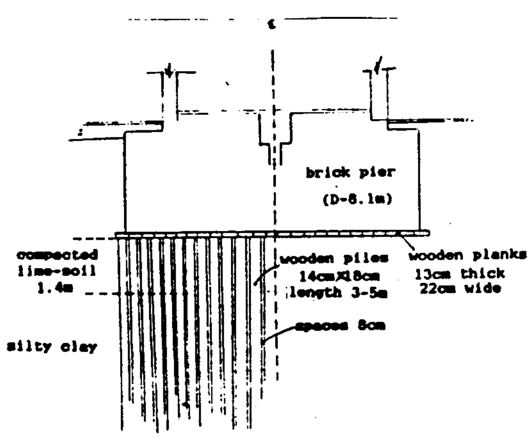

Fig.57 Pile foundation of Long-hua pagoda

Wooden piles of rectangular cross section 14x18cm were driven at 8cm interval under the entire pier with wooden planks 13x22cm placed on top of piles, forming a platform for erecting the brick pier.

This is the earliest pile foundation ever discovered in China.

8. ACKNOWLEDGEMENTS

The authors are indebted to Prof. Zhou Jing who suggested and unceasingly encouraged the preparation of this paper. They also want to acknowledge the contributions of Prof. Cheng Qing-Guo, Mr. Wang Ji-Tang, Mr. Kong Qing-Hua, Mr. Zhong Shi-Hang and Mr. Shi Zhen-Hua who generously supplied the materials they have or gave clue to where needed information could be found.

Materials contained in published works such as those listed in the references were freely extracted and used in the paper. The authors would like to express their gratitude to the original authors.

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