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The history of geotechnical engineering up until 1700

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FOREWORD

It will come as no great surprise to learn that the development of geotechnical engineering up until the end of the period assigned to me - 1700 - was through a succession of experimentations without any real scientific character. Indeed it could not have been otherwise when, at the beginning of the 17th century, the most advanced minds of the age discussed concepts without providing a definition: Galileo and Descartes both make reference to the ideas of speed and of distance moved without firstly stating what is meant by the words used. Before that time we find only a set of empirical rules, and in that which follows the reader will search in vain for any mathematical equations or soil mechanics formulae. In this respect I stand to discourage all those who are disciples of logic and rigour.

If, therefore, we are concerned only with the history of the development of techniques, I shall however have the opportunity to show you how these techniques have advanced at certain periods in history, and sometimes their remarkable refinement, witnesses to careful observation and study, and to gifts of imagination and intuition. So often, alas, these brilliant ideas have not been successfully passed down, and have become lost in history.

If I am to be restricted to a period which ends only at the dawn of the scientific era, I have nevertheless the advantage of being able to review a very long period of time. It will be possible, consequently, for certain particular monuments (the Pyramids, the tower of Pisa, and a number of other famous structures) to look at the question of long-term deformations, one of the least explored areas of our discipline.

Many a proud fortress and many a great city have long since crumbled through being badly founded. Those ancient structures still standing carry a message, which it is for us to decipher.

I - GENERAL.

1 - General knowledge concerning soils

The first treatise on geology did not appear until the end of the 18th century (1); beforehand our subject of geotechnical engineering was of no more than a succession of experimentations of an inexact nature and lacking any scientific character: indeed the ancient Greeks accorded supernatural properties to stones and other inorganic matter for they considered them as forming a part of the living world. The rock aetites for example was to them of great importance: "That which comes from Africa (2) is slight and malleable, it carries in its heart a clay which is soft and white; it is friable and is considered as female; the male equivalent which comes from Arabia is strong and bears within itself a hard stone." Behind these rocks lived a god, Poseidon petraios, who manifested his anger by provoking earthquakes. Poseidon the breaker of rocks.

Thus the Greeks classified rocks on an anthropomorphical basis, according to the apparent gender, and their ability to change and form other rocks. The philosopher Seneca pictured the earth as a living creature. It is not until the 18th century that we find an end to such superstition. Thus Linné states that (3) "Rocks are solid bodies, they are not living and they have no senses."

Nevertheless, despite holding such beliefs which we find amusing, the Romans appreciated in certain soils a property fundamental in geomechanics; the phenomenon of friction. The historian Vitruvius remarks upon the superior nature of quarried sand, particularly "that which grates when rubbed between the

(1) James Hutton (1795) - Theory of Earth
(2) Aetitae lapides... magnam famam habent: in Africa nascentem pusillum ac mollem, intra se uelut in aluo habentem argillam sauem candidam. Ipsum friabilem feminei sexus putant, marem autem qui in Arabia nascatur.. in aluo habentem durum lapidem - Pliny the elder, Book XXXVI - 149.

(3) Lapides corpora congesta nec viva, nec sententia - Linné (1701-1771).

fingers", when compared to an earthy sand which lacks roughness (non habebit asperitatem II 4-1); Pliny for his part advocates sand which is clean and angular (harenae purae asperae. Book XXXVI-L II).

Further back in history the delta civilisations (of Mesopotamia, the Nile, the Indus), who used sun-baked bricks for their buildings, had developed an empirical appreciation of the properties of silts; the possibility of compacting them by treading at certain water contents, the existence of two shrinkage limits, reversible and irreversible, and the ability to reduce shrinkage by forming a mixture with dry straw; in using smooth surfaces for sliding blocks for construction of the Pyramids or for raising an obelisk the Egyptians learned the difference between the friction generated for stone sliding on sand and for stone sliding on wet silt.

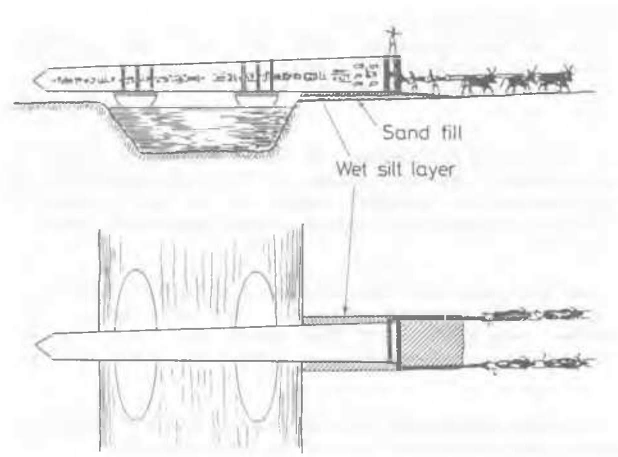


Fig. 1 - The use of a smooth surface for sliding on silt for raising an obelisk

2 - Regulations and treatises

Apparently the first "Building Regulation" concerning the soundness of a structure belongs to the reign of Hammurabi, King of Babylon between 1728 and 1686 B.C. The silts on the banks of the Euphrates led to many difficulties with the foundations of the buildings and this ruling, frequently called into use, followed the principle of an eye for an eye, in that the death of the owner due to collapse of his dwelling required the putting to death of the builder, the same principle passing through to the respective descendants.

Rather more poetic are the Hindu set of rules Manasara Shilpashastra written in Sanskrit, by an unknown author. Their age is uncertain but they would date at latest from the 7th century A.D. and at earliest from one or two centuries before Christ. The requirements of Chapter XII, concerning foundations, include:

47 - The correct architect shall wash the excavation with the five products of the cow.

52-53 - He shall wear his finest robes and offer to the God of the Universe incense and flowers. He shall give himself over to meditation.

212-213 - The Chief Architect shall use male bricks for the construction of temples consecrated to male divinities.

214 - The excavation shall be dug during the night and the bricks shall be laid by day.

With regard to buildings and structures we will have reason to quote some regulations which are considerably more detailed. Due to the wide interest aroused the book has been translated into English (1).

It is an open question whether the Manasura Shilpashastra was inspired by the work of Vitruvius, who was writing around 25 B.C., or vice versa: one finds a number of similarities between the two books in their requirements for shallow foundations. In either case we can recognize the work of Vitruvius as the most important document on the architecture of ancient civilisations, and in it we find numerous interesting references concerning foundations.

The Chinese law Ying Zao Fa Shi, drawn up over a period of thirty years by a certain Li Jie, was enacted in 1103 A.D. during the Sung dynasty. It contains 3 555 clauses. It has the peculiarity of including some remarkable rules for the design of wooden structures to resist earthquake forces. Foundations are no less well treated, as we shall see later.

Experience of construction in Egypt led to the appearance of the document Kitab al Ipadah wa'l I' tibar (2) in Cairo in the 13th century A.D. The book is one of guidance and warnings, and includes in particular a description of the procedure for constructing foundations under water, known as zarbiyyeh (see Chapter V).

During the Renaissance a number of treatises were published in Europe, of which the best known is that of Philibert de l'Orme. The book was first printed in 1561 under the title "Inventions for Good Construction, and at Low Cost" and includes a study of foundations on caissons and on arches, under water and by the sea.

Finally, as the 18th century approaches, we come across the publication in France of "Les Oisivetés" of the Maréchal de Vauban. Of a total of twelve chapters the eighth concerns "The Attack of Fortified Cities", the ninth "The Defence of Fortified Cities", while the eleventh is devoted to earthworks. Also included are 143 maxims "recommended to be

(1) Architecture of Manasara.
(2) Translated into English under the title The Eastern Key - 1964 - George Allen and Unwin.

followed by all who wish to build" where the author offers his advice and experience drawn from a career which included construction of over thirty forts and countless retaining walls, covering the whole range of civil engineering from foundations to carpentry.

3 - The importance of foundations to our ancestors, and their mystique

In civilisations throughout the world the earth has been revered as the mother who feeds us, and the stars, particularly the Sun, symbolised as a divinity. It is not surprising, therefore, that the ceremony of founding a religious structure, or even a dwelling, has been accorded a certain solemnity and has acquired a certain mystique.

In India, for example, the purpose of the rituals described earlier was to draw together the magical forces contained within the ground and to utilise them to construct a support for the dwelling in which man would live in harmony with the rhythm of the cosmos. In contrast the tumulus or the burial pit signified the return of man to the earth.

One finds the same significance attached to this link with the ground throughout the world. In Australia for the Kamilarois a simple post fixed in the ground, although emerging from the soil, represents as much a source of union with the depths of the earth as it does a connection with the sky. In India a temple carved out of the rock (one finds numerous examples with three entrances) provides the link between the spiritual and the entrails of the earth. Similarly the ancient Chinese would take careful precautions prior to building their houses and would avoid any site where some natural cavity existed for fear that it might be an orifice from which the earth spewed out devils.

The well-constructed foundation provides not only harmony to the structure. Philibert de l'Orme writes: "The beginning is of such great importance that if the first foundation blocks are not perfectly positioned, square and level, the rest of the structure will not be without some deformity, and one fault will lead to many others." On the other hand it is generally held that a firm foundation will lead to prosperity. We read on a cylinder excavated at Sumer: "Once the foundations of my temple are completed you will lack for nothing... fertility and oil and wool and water will gush forth from the bowels of the earth." Consequently we find great importance attached to the founding ceremony down through all the dynasties of the Egyptian Pharaohs, as for example portrayed on carvings of the temples from the period that followed the New Kingdom.

We learn that under the 3rd dynasty the Pharaoh himself took over the role of marking out the corners: the soil having been turned over by picks, the king dug the trenches and marked the foundations by filling them with white sand, a symbol of purity. Finally, following a custom handed down from the time of the first buildings constructed in brick, a cake of sun-baked mud from the Nile mixed with seeds of incense was placed at each of the four principal corners.

From a later date during the reign of Sesostris I, a papyrus provides a description of the procedure followed for the construction of a temple at Heliopolis. The choice of a site was decided by debate between the high-ranking officials, presided over by the king, and the decision passed down to the senior members of the corps of architects by the Lord Chancellor. Then the king, armed with the casket of the Divine Scroll and dressed in ceremonial robes, proceeded with the high priest to the chosen site for the foundation ceremony. This occasion was governed by a complex set of rules, demanding careful preparation in minute detail, and was of a particularly solemn character.

Whereas the act of founding a building was indeed of important religious significance, it is clear that the event also had political motives, demonstrating to the people the everlastingness of the dynastic order and confirming the close links that existed between the king and the gods.

II - FROM PREHISTORY TO HISTORY .

Our subject begins before human records, in the mists of time, back to the age which we term prehistory. Man first appeared on the earth some millions of years ago: the two oldest skeletons so far discovered are those of the woman given the name Lucy, discovered in Abyssinia, and the most ancient of all discovered in Tanzania by Dr. Mary D. Leakey. Table 1 details certain landmarks in the history of the human race. All in all the Paleolithic accounts for more than 98% of the duration of the existence of man and hence this period, and even before, merits further attention.

According to the specialists in prehistory (Nice conference on hominisation) earlier than five million years ago apes had already learned to construct habitations on stilts. Everyone knows the story of the chimpanzee, the inventor of the penetrometer, who carried out in-situ tests on termite mounds: he knew how to select his stick, to trim it to the correct length, to force it into the small hole in the termite mound and then to draw out those termites who had caught onto the stick in self-defense, and to munch them one by one.

Similarly there is the account of the elephants in India used for compaction of the clay core of an earth dam by treading. Being mistrustful by nature they would only move very warily onto the area to be compacted having firstly carried out two in-situ tests, the first using their trunk as a penetrometer, and the second by kneeling on the edge of the compaction area.

These examples and others suggest that invention in animals is of the same nature as

TABLE I

LANDMARKS IN THE HISTORY OF MANKIND

Years	Period	Epoch	Subdivision	Culture	Hominids	Landmarks
0	QUATERNARY	HOLOCENE		NEOLITHIC		FIRST METALLURGISTS FIRST FARMERS FIRST HERDSMEN
> 10 000		PLEISTOCENE	UPPER	PALEOLITHIC UPPER		
> 20 000					(CRO MAGNON)	
> 50 000				MIDDLE	HOMO SAPIENS (NEANDERTHAL)	MAN BURIES HIS DEAD
> 100 000						
> 200 000			MIDDLE		(TAUTAVEL)	FIRST SETTLEMENTS IN THE OPEN AIR
> 500 000					HOMO ERECTUS	
> 1 000 000			LOWER	LOWER	HOMO HABILIS	FIRST CONSTRUCTED DWELLINGS
> 2 000 000	TERTIARY	PLIOCENE				MAN FORMS THE FIRST TOOLS
> 3 000 000					AUSTRALOPITHECUS AFRICANUS [LUCY (ETHIOPIA)]	
> 4 000 000					[MARY LEAKEY (TANZANIA)]	
> 6 000 000						

invention in human beings, that there is no unbridgeable gap between the two, and that animal instinct includes an appreciation of the different strengths of different soils.

The evolution of the hominoids has been shaped partly by their relationship with the soil: below we develop three aspects of this subject.

1 - Ichnology and the aid of soil mechanics

The various parts of the human body and how they are put together are no accident, they retain equilibrium in transferring to the ground the gravitational forces that act on the body as well as optimising the normal and tangential forces and the moments which can be developed in flight or in the chase.

Those of an inquiring mind cannot help but be struck by the stance of the human being, its straightness and uprightness. Fig. 2 demonstrates how the hand has developed little between monkey and man in contrast to the development of the foot.

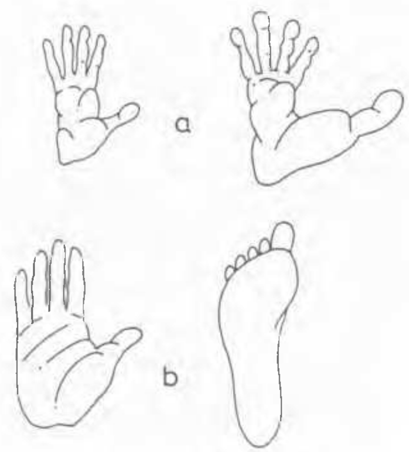


Fig. 2 - Hand and foot a) of the monkey
b) of the human being.

The human foot, in its finally evolved form, fulfils the double role of carrier and propellant.

While upright and at rest man is either taligrade (Fig. 3) on firm ground, exerting the maximum bearing pressure on the supporting soil, or plantigrade with a triangular form of support ensuring good transverse equilibrium as well as reducing the applied bearing pressure in comparison with the rectilinear condition.

The metatarsal bar BC provides the means of ensuring transverse equilibrium, while the stresses acting on the arch of the foot are transmitted to the soil at A and C without a tangential component.

When in motion the human being becomes digitigrade; the weight is transferred to the front of the foot and in soft soils the toes sink in up to the joint c, particularly at the root of the big toe, the hallux valgus. The tangential force applied to the soil which was directed forward at the moment of contact becomes reversed at the moment of lift off leaving a strong imprint in the soil and a surface of rupture R in the case of a strong push on a weak soil (Fig. 3).

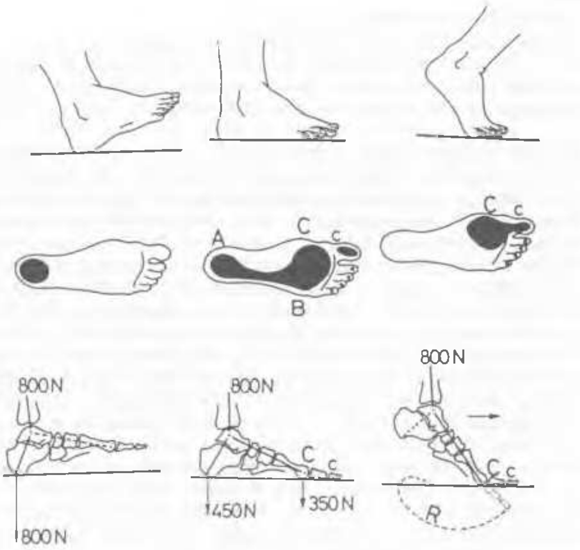


Fig. 3 - The three upright postures of man.

The scientific discipline of ichnology, created by H. Duncan in 1828, is the study of imprints left in the soil by members of the animal kingdom. The oldest human footprints yet discovered were found by Mary Leakey in the Laetoli plain in Tanzania (Fig. 4), not far from a volcano. They have been miraculously preserved, for the man walked on a layer of volcanic ash which, due to a fall of rain just before, possessed a certain cohesion, the footprints being covered by a further layer of ash soon afterwards which then hardened. The outline of the footprint resembles that of modern man. The imprint of the hallux valgus is very marked. The evolutionary development from a) to b) of Fig. 2 had already taken place giving the man the ability to set off quickly when threatened by predators. Contrary to that which is indicated in Column 3 of Table 1, drawn up following the classically accepted sequence, homo erectus already existed 3.6 million years ago.

Soil mechanics, through ichnology, is therefore also of relevance to palaeontology, not only in the study of the footprints of hominoids, the very oldest or those more recent (Cave at Foissac, France - Garcia and Dunday 1983), but also of other animals (such as the dinosaur footprints found in the cretaceous rocks of the Bolivian Andes or near the Niger - Appendix I).

2 - Homo faber had an appreciation of geology and rock mechanics

Homo faber developed a knowledge of the hardness of different rocks and of the planes of weakness he should attack in forming his tools.

The stone implements found in large numbers in caves and elsewhere are not merely a collection of different forms to be categorized: each was shaped for a particular individual purpose. I would imagine that the tool shown in Fig. 5 was one of the first developed for digging the earth, or perhaps for breaking up weak rock - the precursor of the rock bit. Thus man had invented the first tools, coming from the earth, and the first techniques for digging the soil.

The rocks most frequently used for forming tools were veined quartz, rock crystals, chert or hard sandstones. The method of shaping the implements was to strike one stone against another at an angle. The choice of the type

Fig. 4 - Oldest human footprints, discovered in the Laetoli plain in Tanzania. (See also Appendix I). By permission of Dr. Mary Leakey - Photo J. Reader (Nat'l. Geographic (1979).

Fig. 5 - The precursor of the rock bit wielded by prehistoric man . P.Vaughan (1983)- By permission of " La Recherche " .

of stone as well as the techniques used for forming the tools are important indicators of the progress of man's development.

3 - Homo sapiens had already a perception of the long-term stability of caves

It appears that the caveman had already gained an intuition for the manner in which the stresses were developed in the rock mass above his head. How else can one explain the series of parallel lines in the form of an arch (Fig. 6) found inscribed in a crevice in the cave at Font de Gaume, in the Dordogne region of France.

Fig. 6 - Cave at Font de Gaume - Shape of a barrell vault symbolising the effect of buttressing .(Reproduction authorized by la Conservation des Monuments Historiques pour l'Aquitaine) .

Close to Peking, at forty kilometres to the south west, is the cave of Zhoukoudian. This great cavern, at one time over 140 m long, was inhabited for a period of over 200 000 years, from 460 000 to 230 000 B.C., by Homo Erectus Pekinensis - Peking Man.

The cave is situated in a region of karstic limestone. Geologists believe that the formation of the cavity began some 5 million years ago. The technique of radioactive-carbon dating allows us to trace the history of the use of the cave by human beings. Peking man first set up home in the cave around 460 000 B.C. when erosion by the river flowing along the east side of the hill formed an opening. A large rockfall in the eastern around 300 000 B.C. forced the cave dwellers to take refuge in the western part which was accessible through a crevice in the limestone.

By the time it was abandoned, around 230 000 B.C., the cave had become filled with debris from minor rockfalls or the detritus resulting from human occupation. It is possible to distinguish 10 different layers in this debris in which have been discovered the remains of 40 individuals, male and female of various ages, as well as their utensils. It appears that over this period the humans evolved very little in their adaptation to the soil, that is in the form of the feet, while the size of the brain increased steadily from around 1 050 cm^3 to around 1 150 cm^3. The tools from the period 460 000 to 420 000 B.C. are relatively large and formed from comparatively weak sandstone. In contrast those from the period 300 000 to 230 000 B.C. are smaller and are of quartz, or occasionally chert. Their knowledge of the behaviour of rocks had greatly improved.

Thus Peking Man lived over a graveyard and beneath a roof that was prone to rockfalls, which explains why, in those caves inhabited at a later stage, we find evidence of internal improvements. Thus if the roof was liable to instability the caveman started to erect structures similar to the dwellings which he had begun to construct in the open air. Furthermore we know for certain that the artists who produced the paintings in the cave at Lascaux, in France, erected a scaffolding for the marks left by the supports are still visible.

4 - From the first tumuli to earth dams

The first earth structures had a religious motive and date from the Neolithic or possibly the Upper Paleolithic, that is well before the Iron Age: stone implements or animal horns were used for digging the earth.

At a later stage the purpose of the structures was generally utilitarian: irrigation channels for agriculture, flood protection of individual houses then villages by trenches and levees, reservoirs, the realignment of rivers, and later embankments and ditches for protection against invasion, earth dams but always erected in homage to a god, so retaining their religious significance.

4-1 - Earth structures as religious monuments

The new buildings of importance, palaces, religious monuments, would be constructed on foundations built with the debris from former structures or walls, mixed with earth and compacted, the construction of different ages being piled on top of each other in successive layers, as verified by radioactive-carbon dating. Let us take a typical example borrowed from the history of Mesopotamia.

The excavations at Ur, in 1933, under the supervision of the archaeologist Sir C. L. Wooley shed some light upon the nature of the great earthworks built to support religious monuments, from a period far back in history: Ur was situated at the former mouth of the river Euphrates and around 2300 B.C. became the capital of the Sumerian civilisation. At this time the king Ur-Nammu undertook the construction of a great esplanade dedicated to the moon god Nanna. The ramparts forming the periphery of the esplanade were built from bricks of sun-baked mud (adobes) (1) laid with a mortar of mud and with an outer covering of fired bricks (2) (stamped with the name Ur-Nammu). This outer face had a slope of 45° and the ramparts were no less than 22 m wide at the base for a height of 8 m. In several places the fired bricks have been stolen and with time the slope of the outer face has been reduced. Decorating the face of the ramparts are a series of buttresses (greater than 2 m wide) built from fired bricks with a brick foundation, which are continued into the interior of the esplanade forming a honeycombed structure to better resist the earth pressures and the weight of the heavy structures built above (a ziggurat among others). The sequence of construction was to build the ramparts and the interior walls and then to place compacted fill in between. Recently a number of cylinders have been found bearing inscriptions describing the operations, although as yet it has proven impossible to translate them completely (Lagash). The English version of the incomplete German translation is as follows: "The soil .... ? .... to a depth of .... ? ....and if he excavates it, this earth as a solid rock he .... ? .... and as a pure metal (silver) he .... ? .... with fire." According to Wooley and his co-worker the words used imply a sort of purification of the soil by fire so as to refine it like pure silver and to render it as hard as rock.

Among the discoveries during the excavations at Ur are certain unusual caissons and drains whose functions are difficult to explain. Beneath a number of religious monuments and altars have been found wells which are filled either with fired bricks or unworked blocks of rock: these caissons were covered over by a paving on which the structure was built, and it is as if the sacred character of the building depended on the sacred nature of the foundations, built from a material purified by

Fig. 7 - A vertical drain dating from Ur prehistoric period . Sir C.L. Wooley (1933) - By perm. of the Antiquaries Journal .

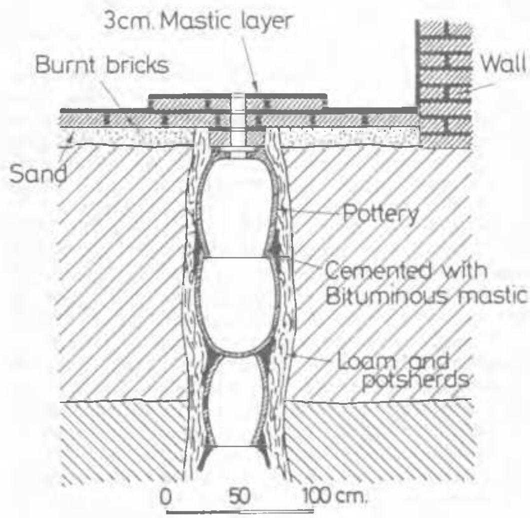


Fig. 8 - A domestic drain from the Kassite period (1500 B.C.).

(1) According to G. Sowers the unconfined compressive strength of such materials, used to a greater or lesser extent in much the same form by all the ancient civilisations, lies within the range of 100 to 700 kPa, meaning that the maximum possible height of a wall before the onset of plastic deformation would be some 15 metres.
(2) Obviously the temperatures in these furnaces were much less than those found in a modern furnace. According to Rathgen (1913) the temperatures would have been no greater than 550 to 600° C, producing rather porous bricks which were then placed in a bath of bitumen, much used in Mesopotamia, absorbing some of the bitumen into the pores.

fire or from rock that had not been contaminated by the use of metal.

Beneath the houses built on the esplanade an astonishing quantity of vertical drains have been discovered, of the type shown in Fig. 7, whose presence cannot be satisfactorily explained by the domestic requirements of the building. The most plausible explanation according to Wooley is that the drains were a medium for passing drink-offerings to the gods of the underworld, another example of symbolism in foundations. Fig. 8 shows a domestic drain from a later period, the reign of the Kassites (1500 B.C.), which is of a more conventional form compared to those of the 3rd dynasty.

The largest surviving earth structure in Western Europe, built entirely by human labour, is Silbury Hill in England: the base covers an area of 20 000 m^2 and it is 40 m high.

The earliest known tumulus to be built in China was the resting place of the emperor Shih Huang Ti of the Ch'in dynasty (around 200 B.C.). It was he who oversaw the construction of the Great Wall of China. His burial mound was enormous having a square base of side 300m, although the height of 150 m traditionally attributed must be an exaggeration bearing in mind the steepness of the slopes required.

On the American continent a large number of ruins of earth structures dating from the pre-Columbian period have been discovered; they have been well chronicled by G. Sowers (1979) who has demonstrated their different aims: defence, effigy or platform, giving way progressively to the American pyramids of compacted earth. The oldest of these structures are found in Peru and date from 1800 B.C., and they continued to be developed through to the end of the first millennium A.D. The largest Peruvian pyramid, the Temple of the Sun at Pachamac, built in adobe, is only 23 m high however.

The oldest earth pyramid in Central America is that at La Venta in the lowlands of the Gulf of Mexico, built by the Olmecs around 800 B.C. The structure has a rectangular base measuring 130 m x 65 m and a height of 35 m. The side slopes of the north and south face are at an angle of 30° and lead up to a platform at the summit measuring 12 m x 12 m. The bulk of the pyramid is of sun-baked brick, with a facing of stone. The largest pyramids in the region are located in the Valley of Mexico: the largest of all is not dedicated to the Sun but is the Temple of Tepenapa, built in stages over the period 350 A.D. to 600 A.D. It has a square base measuring 402 m x 402 m and reaches a height of 70 m. It is constructed from large blocks of tuff placed in a matrix of earth mixed with volcanic ash. An archaeological dig by means of a tunnel has revealed the presence of five or maybe seven concentric pyramids. With a volume of 3 700 000 m^3 this pyramid is one and a half times larger than the stone pyramid of Cheops, although this latter with a height of 150 m exerts a far greater bearing pressure.

4-2 - Dykes and levees

In the basins of large rivers where flooding led to the formation of rich soils alongside the river banks, the development of the first human settlements saw the construction of the first dykes and levees. Table 2 summarises details of four of the largest of these regions. The purpose of the dykes was to protect the settlements from flooding. In parallel a network of canals was contructed for irrigation.

Thus several thousands of years ago civilisations were able to alter the natural terrain and hence bring about great benefits. Such was the case in Egypt when the Pharaohs decided to move from Thebes in Upper Egypt to create the new capital of Memphis, located on the left bank upstream from the head of the delta (about 35 km south of Cairo), from where they could survey the two Egypts. By 3000 B.C. it proved necessary to protect the town from flooding from the Nile, by means of a dyke 450 m long. This embankment was 60 m wide at the base and had a height of 15 m. The last of the pharaohs of the Middle Kingdom, Amenemhet III (around 1700 B.C.), was an accomplished hydrology engineer and completed the protection of Memphis by improving the course of the Nile in constructing a canal further to the north on the left bank deviating the river towards Lake Moeris.

In Mesopotamia the Sumerians built a great network of dykes and canals to divert the water towards regulating reservoirs. At a later period the Greek historian Strabo provides an account of the difficulties the Sumerians had in the up-keep of the network: "The soil is so deep and soft, it yields so easily that the trenches and canals are wiped out by the river in flood. The canals become filled in or silted up and the plains near the coast become lakes and marshes filled with reeds." It goes without saying that the construction of the works on such soft and compressible soils was far from easy. The fine silty material would punch into the underlying soil and already one comes across the use of blankets of reeds as soil reinforcement. Nevertheless the network survived, the life-span of the dykes depending upon the politics of the day and the sedimentation of the river. Aerial photographs reveal the presence of numerous former canals and reservoirs but it is difficult to recreate the rest of the network due to the continuous silting up and settlement of the region.

Possession of the irrigation network was the goal of many attempted invasions, since it brought about prosperity. Through philology we learn how the kings won fame through their construction achievements: Ur-Nammu left a list of the canals that he had built; Hammurabi of Babylon (1700 B.C.) undertook the construction of a canal joining the Tigris and the Euphrates; Sargon II (710 B.C.) by the construction of irrigation canals created the gardens of Niniveh. Alexander the Great

TABLE II

CHARACTERISTICS OF THE RIVERS OF THE BASINS OF FOUR ANCIENT CIVILISATIONS

	EGYPT	MESOPOTAMIA	CHINA	INDIA
River	Nile	Tigris and Euphrates	Huang Ho (yellow river)	Indus
Annual Rainfall (mm)	250	200	500	250
Source	African lakes and Abyssinia	Mountains of Armenia	Kunlum Mountains	Hindu Kush and Himalayas
Flood rise (m)	5-7	5	4-7	4-5
Percentage silt	0.17	0.75	1 to 2	0.43
Type of silt	Clay with up to 20% sand	Calcareous loam	Loess	Fine clay
Gradient	1:13 000	1:26 000	1:35 000	1:7 000

appreciated the importance of the up-keep of the canals, and based on a text of Strabo appears to have been an able geotechnical engineer. "Aristobule says that Alexander himself, while piloting his boat, inspected the canals which were then dredged behind him. He noticed that the entrance of one canal, that which flows towards Arabia, was silting up and was proving difficult to maintain because the soils were so soft and compressible; he decided, therefore, to open up a second entrance at a distance of 5 km, having chosen a site where the bottom is rocky..."

Upstream from the delta, where the large cities developed and where the soils were less treacherous, the dykes constructed were much more sophisticated. Many noticeable examples are found at Ashur, such as that built by Adad Nirari around 1300 B.C. flanking the Tigris over a length of 1 500 m. The works were carried out behind a cofferdam (1). The dyke itself comprises a wall of limestone blocks with bitumen placed along the joints, protected on the river side by a wall of fired bricks linked to the main wall by buttresses 5 m long and 1.5 m thick, these themselves being linked to each other behind the wall; the whole of the brickwork receiving a coating of bitumen (Fig. 9).

There is often evidence of repair works having been carried out (Fig. 10). These structures suffered settlement or were destroyed, often due to insufficiency of the foundations, the

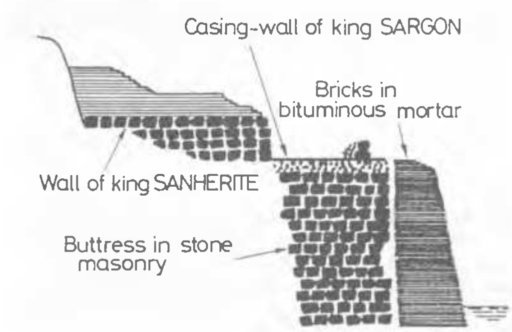


Fig. 9 - The quay at Ashur, 1.500m long flanking the Tigris - Andrae W. (1913) .

quay at Ashur being undermined by a river, other quays being constructed on top of the old.

The invasion of the Mongol hordes in 1258 A.D. followed by the systematic destruction of the canals and dykes led to the rapid decline of the Mesopotamian civilisation and brought to an end this great period of invention.

A dyke dating from around 2000 B.C. has been found in the basin of the Indus. Its purpose was to protect the town of Mohenjo Dara (2) from flooding. It is built of earth and is

(1) Clay tablets illustrate the use of wood in the cofferdam.

(2) Situated 400 km north of Karachi. This civilisation flourished between 2700 and 1700 B.C.

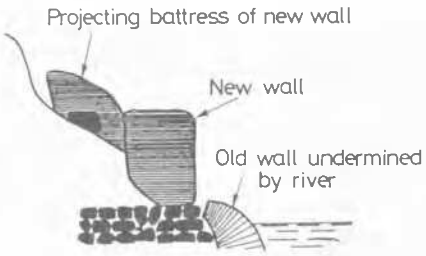


Fig. 10 - Repair works to the quay at Ashur.

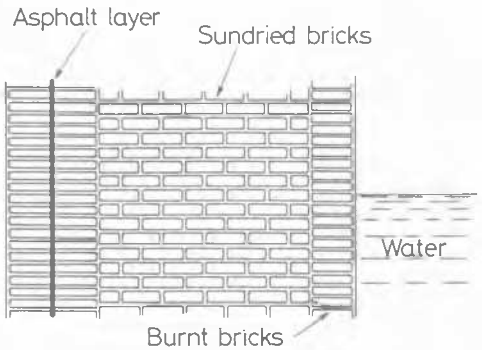


Fig. 11 - Cross section of a reservoir wall at Mohenjo Dara.

1 500 m long. In this region also, for the walls of reservoirs, are found the same construction materials, fired or sun-baked bricks with bitumen for the joints (Fig. 11).

In China irrigation became an important feature of life at an early stage. Often the dykes were provided with a protective layer of stone blocks or fascines, but no measures were taken to ensure a stable foundation, nor to provide protection against erosion from floods, to such an extent that in the picture language of the Chan dynasty (1120 B.C. to 249 B.C.) the character for sluice became synonymous with that for catastrophe.

5 - Dams

The same advances and the same deficiencies as found in the oldest dykes are found in the oldest dams, the principal defect being that they were vulnerable to overtopping, whereas the gentle slopes of the upstream and downstream faces, generally between 1.5 and 2 (h) to 1 (v), were unlikely to give rise to problems of instability.

According to Helms (1981) the oldest dam in the world is that at Jawa in Jordan, built of earth with a masonry facing and dating from around 4000 B.C. The second oldest would be the rockfill dam at Kafara on the Wadi Jarawi, a tributary of the Nile, some 30 km to the south of Cairo. This dam has been described by Schweinfurth (1922) and Murray (1947). It was built around 2600 B.C. and thus is slightly predated by the first stone pyramid, built at Saqqarah, which marks the beginning of the period of construction in stone in Egypt. The dam is 108 m long while the width at the base is no less than 84 m for a height of only 12 m. It comprises two rock embankments (placed without mortar) which mark the upstream and downstream limits of an earth embankment formed from borrow from the surrounding hills mixed with the material of the river bed. There was no spillway included and no cut-off wall. It is likely that the central portion was washed away in a flood. No further attempt was made at dam construction in Egypt in the next 3 000 years.

The oldest dams found in America are from a much later date. Two that are notable are the one on the Lencho Diego Creek in the Tehuacan valley, built over the period 750 B.C. to 600 B.C., and the dam at Purron built in 600 B.C. with a height of 3 m and successively raised to 7, 10, 18, and 19 m (Fig. 12) as the reservoir behind silted up. A cross section reveals a honeycombed masonry structure filled with a compacted sandy material. The upstream facing is of masonry.

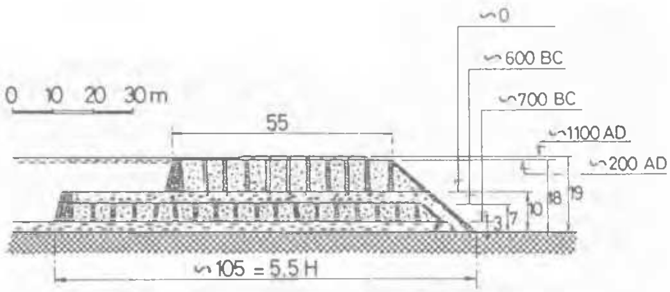


Fig. 12 - Successive raised levels of the dam at Purron from 700 B.C. to 1100 A.D. after N.J. Schnitter (1982).

The oldest dam in China is that at Shaopo in the province of Anhui (600 B.C.).

It would not be possible to trace a complete chronology of the oldest dams, particularly since so many have been destroyed by floods. However, of those which have survived to the present age heights of 10 m are not untypical. Dams even as high as 30 m did exist.

III - SHALLOW FOUNDATIONS

Let us turn now to the problem of shallow foundations for buildings of all types, for

Fig. 13 - The ziggurat at Aquarquf (left) - Bed of reeds (right) held by D. Parry (right) - Photos D. Parry.

dwellings, religious structures, monuments, etc... and find out what solutions were adopted by the ancient civilisations. With the materials that they used for construction it is clear that the requirements for the superstructure and for the substructure were closely related since the deformability of the former led either to tangential forces acting along the base or to overturning moments. It will be necessary, therefore, to consider the design of both the one and the other.

1 - Foundations on compressible soils

The earliest examples of shallow foundations on compressible soils come from archaeological digs in the delta regions, such as those at al 'Ubaid in Mesopotamia. The walls of the houses were built from plaited reeds curved into an arch and with a coating of bitumen to fill in the holes; the same reeds as we have mentioned above as used beneath the dykes on the banks of the Tigris and the Euphrates. Obviously these structures were very light and flexible and the only foundation required was a bed of reeds. In the Nile delta the Egyptians, for their part, were using papyrus and water willow. Thus we see, from the earliest periods in human history, from the time of construction of the first dwellings, that architecture was truly the harvest of the soil: the first source of materials was the vegetation (reeds, wood), then different uses for the natural sources of bitumen were discovered; later the silty soils were used to make sun-baked bricks. It was only very rarely that rock was used and even then only well upstream from the delta.

Nevertheless their religious beliefs and their polytheistic philosophy inspired the delta inhabitants, or at least the Mesopotamians, to erect more adventurous, heavier structures in homage to their gods, which, bearing on the soft soils of this region, led to many difficulties. The most important type of structure was the ziggurat: this was a great mound of a number of tiers built of sun-baked brick, with relatively steep average side slopes leading up to a platform on which was constructed the temple: they reached great heights above the surrounding terrain and the dwelling place of the gods was thus protected from floods and was visible from afar.

As we have already seen, where the height of a structure exceeded 15 m the bricks would have begun to deform plastically. An early discovery of the ancient civilisations was that by adding straw not only could cracking due to shrinkage be reduced but also, and more importantly, a certain tensile strength could be imparted to the bricks. Going a stage further, and showing an excellent understanding of the problem, the Sumerians came up with the idea of placing at intervals a layer of matted reeds between the layers of bricks. In this way the structure might settle, but as a solid block without lateral extension.

With time the soils beneath the structures consolidated causing settlement and resulting in an increase in strength. Often the Sumerians constructed other temples on top of the old as for example at Eridu, the oldest holy city in southern Mesopotamia, towards the end of the 5th millennium B.C. At a later stage, at the time of the 3rd dynasty of Ur, a ziggurat existed on the same site, built using the same construction methods as discussed above. Similar ziggurats were constructed elsewhere, notably at Ur and at Uruk. The latter was crowned by the White Temple dedicated to the god Anu, and the foundations of this structure reach to 12 m below ground level.

Fig. 14 - Map of ancient Mesopotamia.

Undoubtedly the most impressive surviving ziggurat is that at 'Aqarquf (1400 B.C.), 32 km to the west of Baghdad. It has steep side slopes of 10:1 and a height of about 57 m. It includes layers of reeds with a covering of sand and gravel between every eighth or ninth layer of bricks. The reeds were bound together to form cables about 10 cm in diameter which were strung at close intervals across the full width of the structure. They are well preserved and are still relatively strong.

These interspersed layers played an additional role in acting as drains for the dissipation of the excess pore-water pressures built up in the bricks as the height of the structure increased.

From this remarkable invention it is apparent, therefore, that the Sumerians were in some way aware of the problem of the tangential stresses acting in the structure, and one might even go so far as to say that they foresaw the build up of pore-water pressures and appreciated the necessity of providing free-draining layers.

Nevertheless we should not attribute too great an understanding of soil mechanics to the Sumerians. A certain form of plate with a central hole is often found close to ziggurats and a colleague of mine, J. Biarez, tells me that some archaeologists in Iraq see here a means of prestressing the structure. They are undoubtedly victims of an excessive imagination: a more plausible explanation is that they were linked to wooden posts or beams inserted horizontally into the structure. In the same way there are those archaeologists who believe that the founding levels of the ziggurats, where several metres below ground level, have been chosen deliberately in accordance with certain religious requirements.

The use of mats of reeds was not without drawbacks however, for they sometimes caused damage by undergoing spontaneous combustion.

Whereas some ziggurats have survived in better or worse condition to the present day others have long since crumbled. Such is the case with the celebrated ziggurat of Etemenanki in the centre of Babylon, believed to be the Tower of Babel of the Bible. It is estimated that this structure was 75 m or more high, and it probably included seven terraces. With a bearing pressure of 1 500 kPa the completion of this structure on the soft soils existing at Babylon, with the groundwater level close to the surface, was a formidable achievement.

The ziggurat of Etemenanki dates from the time of Nebuchadrezzar I (1130 B.C.) who undertook the construction of numerous prestigious projects in Babylon which, as shown by the German Koldewey, underwent large settlements: in particular the Southern Citadel settled through the height of one full storey. The city of Babylon was approximately rectangular in shape with a perimeter of 8 km and divided into two unequal parts by the river Euphrates. The ziggurat of Etemenanki was approached along the famous Processional Way which crossed the Euphrates on the first bridge ever constructed over this river.

In France the recent excavations of certain Romano-Gallic country dwellings in the Lower Berry region, at the site known as La Pétonniere close to Paulnay, have revealed a wide variety of solutions adopted for founding buildings on marshy soils (50 to 70 A.D.).

In the Middle Ages, for the construction of masonry footings on soft soils, it was usual to place a mattress formed from fascines several decimeters long at the bottom of the excavation. At a later period a flooring

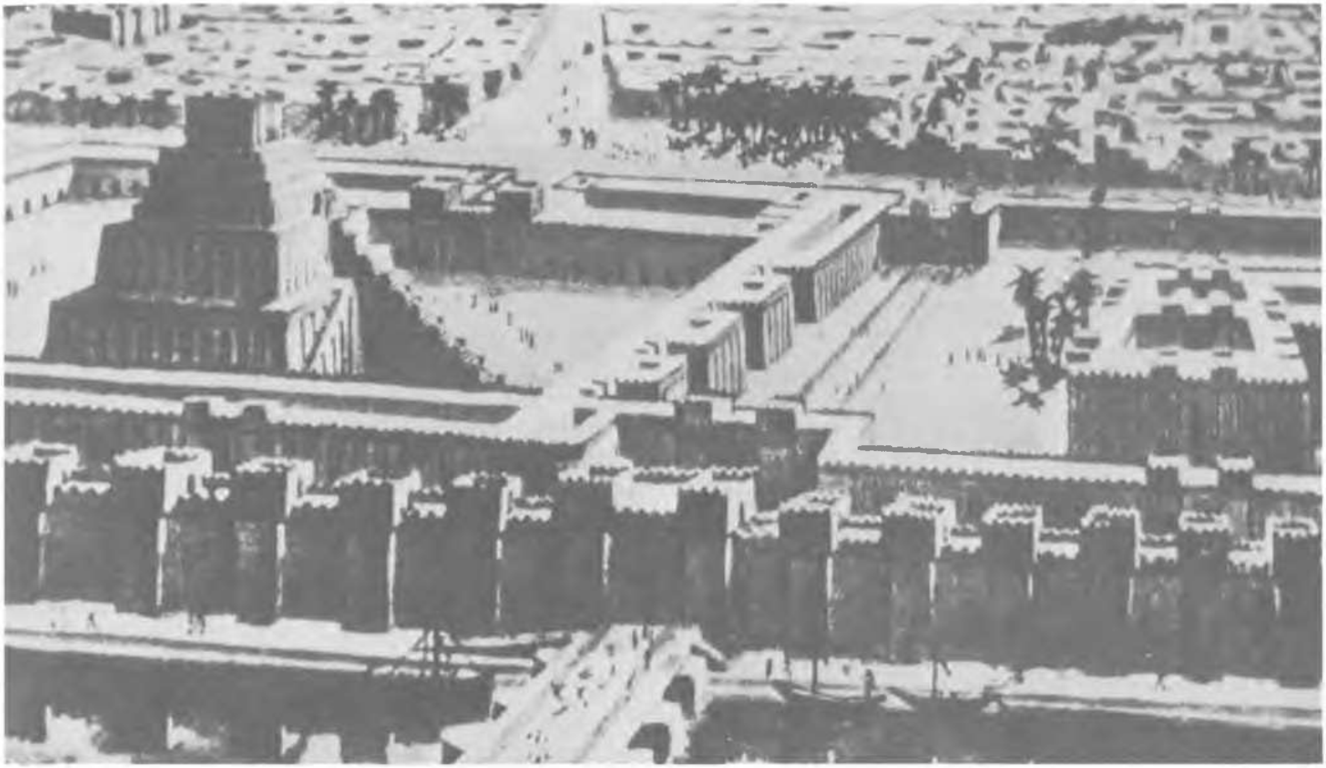
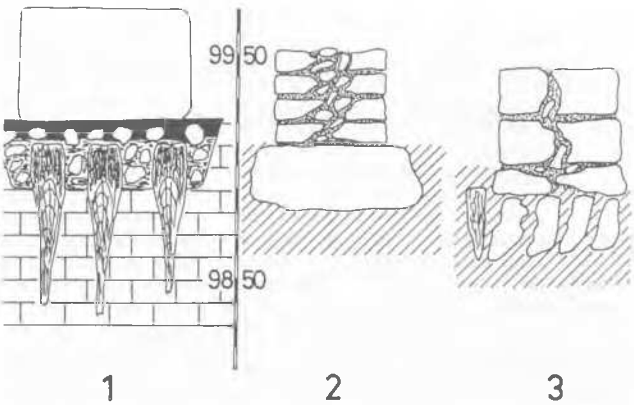


Fig. 15 - Reconstruction of the city of Babylon by Koldewey; the ziggurat at Etemenanki is on the right.



1: piled wall (the black represents a layer of clay that acted as a seal to keep the moisture in, to prevent the piles from rotting) - 2: wall composed of small blocks founded on a large block of limestone - 3: wall composed of medium sized blocks founded on wedges of stone, with, on the left, the original shoring. Drawing by J. L. Girault.

Fig. 16 - Romano-Gallic period - Paulnay (France). Marshy soils. C. Coulon and J. Molmgren (1982).

composed of wooden boards was used. For the construction of the famous Cathedral at Winchester in England, in the 11th century, the excavation was carried down to the water table where beech trees of various sizes were laid side by side to act as the base of the foundation (R. Hammond 1955). A trial hole dug in 1906, by which time parts of the cathedral were badly cracked, revealed that beneath the foundations there existed 1.8 m of marly clay over 2.5 m of peat. The foundations were underpinned by a diver who excavated the soft soil and replaced it with bags of concrete.

Venice, a town built on a lagoon.

My account would not be complete without a mention of the celebrated town of Venice, this town which was the richest and most powerful in mediaeval Europe. Venice is of interest to the geotechnical engineer more for its past than for its present condition for in recent years the rate of settlement of the area has decreased markedly. In past decades settlements, at the rate of several millimetres per year ten years ago, were due largely to the effect of pumping from wells for nearby industry; the application of strict legislation has restored the groundwater regime to its original condition and the rate of settlement has become negligible. Nevertheless the accumulated settlements are sufficiently large that the ground floor levels of the buildings are below the average level of the water in the lagoon, leading to a problem of degradation of the masonry, a situation aggravated by the disappearing shoreline, an important geological phenomenon in Italy.

Of greater interest to the geotechnical engineer are the difficulties encountered in the past, for this centre of culture was founded on unconsolidated alluvial deposits of great thickness. The construction of this town must have been an exciting challenge, requiring an adaptation to the soft soil conditions and an acceptance of settlements up to a certain limit, with the need for careful calculation of the risks involved and for techniques that were not only ingenious but inexpensive and uncomplicated.

The beneficial effect of pre-consolidation beneath existing buildings was used systematically: the old buildings which acted as a precharge were destroyed and the internal walls of the new more spacious building were founded on the same site at ground level. The outer walls would be carried on new foundations of wooden piles. Due to its stiffness this wood was also much used in the outer walls to distribute the loads from the stonework.

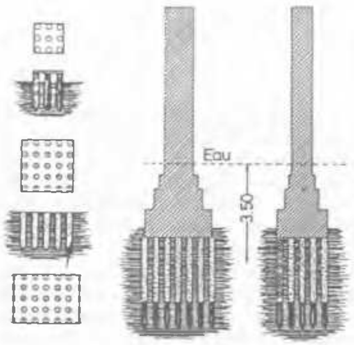


Fig. 17 - Foundations of the outer walls for a building at Venice, after Creazza (1974).

In order to overcome the possible large differential settlements between the internal walls and the outer walls the buildings were designed as isostatic using an ingenious system of adjustment devised by the Venetian architects.

An open-framework style of architecture using arcades and peristyles, that is to say with loads carried by isolated columns, would seem today rather audacious in such difficult soil conditions. However the Venetians not only appreciated beauty but also understood how

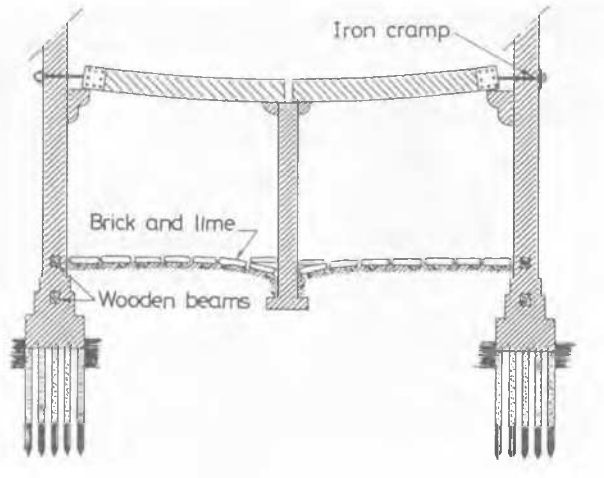
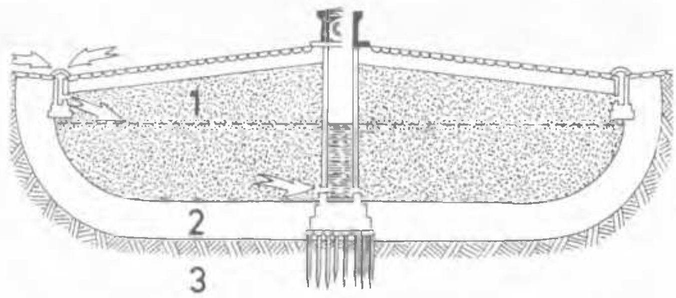


Fig. 18 - Adjustment devices for differential settlement.



1 Filtering sand - 2 Clay - 3 Natural soil

Fig. 19 - Venetian underground tank.

best to arrange the sequence of construction to achieve their ends. Thus for the architraves of the columns they used heavy wooden beams which would deform during construction as the building settled; once the majority of the settlement had taken place the deformation was taken out by an additional course of masonry. The same imagination is apparent in the choice of materials for paving floors which were sufficiently flexible to follow the settlements of the ground (brick and lime mixed together with oil).

Since the water in the lagoon was polluted the Venetians collected the rainfall on the roofs of their houses and led it to underground storage tanks (Fig. 19). The base of the tank was curved and was covered by a layer of clay 1 m thick. Cut into the soft Venetian soils this shape would have been unstable and the sand filling used was as much to ensure stability as to filter the water, which was then led to a central well, whose form could be seen above ground level (Fig. 20).

Fig. 20 - Venetian well.

2 - Common types of foundation: footings, prefabricated slabs, rafts

At Ahrensbük, near to Hamburg, a number of stone circles are still standing which surrounded the walls of the huts of the reindeer hunters who lived in that region around 1200 B.C.; inside this circle the soil has been dug in the form of a trough. Many examples of similar excavations have been found in Russia such as those at Kostienki, Gagarino, on the banks of the Don, at Mezine and at Moldova. In the same way that a bird makes its nest round, man was digging circular holes in the ground for his dwellings; the stones around the houses make it possible to date their construction, which shows that such habitations existed even as early as the Lower Paleolithic. Certain shallow holes that have been discovered, which are the imprints of the bones of mammoths driven into the ground, indicate that the roofs of these structures were supported by a number of individual foundations spaced around the periphery of the hut.

Whereas these ancient dwellings are European, the same form of construction is met in different areas of the world at different periods in history right up to the present day where very similar habitations, with some slight modifications, are encountered in what we call Primitive Architecture (Fig. 21) - (the Indians of Argentina at Pilaga, at Moto Grosso in Brazil, the people of Laponie, in Somalia, in Madagascar, etc...).

With the development of the first settlements the foundations of these structures improved: around 10 000 B.C. small walls 60 to 80 cm high were provided as support around the periphery of the circular excavations. In a recent archaeological dig at Banbo-Cun in the Shensi province of China an agricultural village has been uncovered which, although dating from a later period, from the first half of the 3rd millennium B.C., shows many characteristics that are typical (Fig. 22).

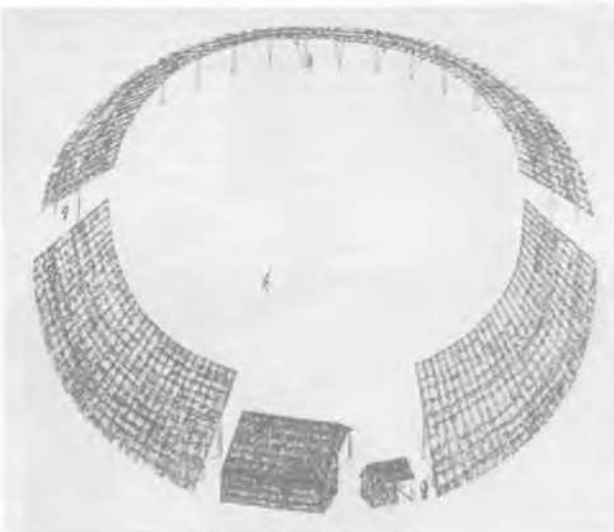


Fig. 21 - Shelters linked together with the chief's hut included in the ring - Amazonas (West Brazil).

Fig. 22 - Banbo-Cun - Shansi: view of the recent excavations.

These huts were either circular or square and the floor level was about one metre below ground level. A large ditch surrounded the huts, providing drainage. Each hut had a central fireplace and around this four holes mark the positions of wooden posts that supported the roof, which probably had a wooden frame (small crosspieces), filled in with straw and rushes and given a coating of clay.

Similarly in Japan this type of dwelling with a circular excavation was typical for most of the Neolithic period. Buildings with a floor level at ground level or higher were not seen until a later period. Around the Mediterranean, again, the circular hut persisted for a long period, but here they were built in stone. Some of the oldest habitations discovered in Jericho, dating from the 8th millennium B.C., had circular stone bases, the structure itself probably being built of clay. From approximately the same time period, at Khirokitia in Cyprus, the huts were again circular with cylindrical walls of stone, and a dome built of brick (Fig. 23).

Fig. 23 - Reconstruction of a Neolithic village at Khirokitia (Cyprus).

The foundations have changed from individual supports to a continuous circular strip footing.

The rectangular house shape is the result of many attempts with various shapes. But rectangular houses did exist as long ago as the second half of the 6th millennium B.C., the dwelling places of the peasants of Central Europe, in Bohemia and Germany: the holes for the posts supporting the roof are on a rectangular grid. In these structures both forms of foundation existed: individual footings for the internal posts, and a continuous strip footing for the perimeter wall.

Egypt

In Upper Egypt where sun-baked bricks were used for a long time for constructing buildings, where the ground was hard it was obviously unnecessary to bury the foundations to any great depth. On the other hand in Lower Egypt and anywhere in the flood plain of the Nile it was necessary, with a few exceptions (see V-3), to dig through the silt deposits and found the buildings on the underlying sand. In times of flood these layers of sand became aquifers linking the two sides of the river, allowing irrigation and replenishing the wells. Each year the Nile has deposited about 1 cm of silt and in Cairo, in excavations 30 m deep, articles of pottery have been recovered that belong to the Thinite and pre-Thinite periods (the 1st and 2nd Dynasties, around 3000 B.C.). The deposits of silt act as a surcharge and hence increase the bearing capacity of foundations. Such was the case at the temple at Karnak where the bases of the 122 outer columns of the hypostyle room became covered by silt to a depth of 4 to 6 metres. Unfortunately the beneficial effect of this surcharge was underestimated and the excavations in 1899 brought about the simultaneous collapse of a chain of 11 columns (Chevrier 1977). It became necessary, therefore, to underpin the other columns by which it was discovered that the original foundations were of blocks of stone known as "talatates". The dimensions of these blocks were standardised to 0.55 x 0.27 x 0.22 m by the queen Hatchepsout, famous for the construction achievements of her reign. The blocks were placed in a matrix of ungraded soil.

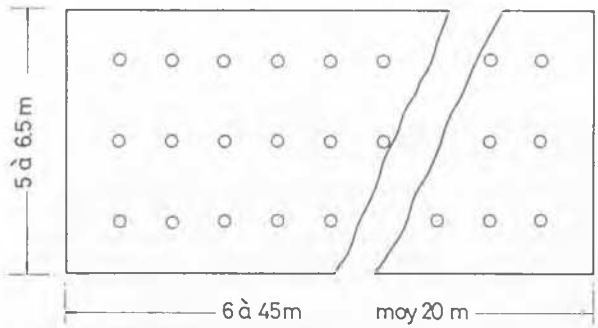


Fig. 24 - Rectangular foundations in Bohemia, with point supports for the roof (VIe millenary B.C).

Ancient Greece

This section, which covers Ancient Greece, also concerns Asia Minor and Crete which both came under the Hellenic influence.

The earliest buildings from this period were still of sun-baked brick, with a wooden framework and resting on a base of rough or shaped blocks of stone. The rooms had larger spans than those of the Egyptians. The transition from mud bricks to stone as a building material was hesitant and the Greek architects were doubtful of the strength of stone blocks. The change came around 550 B.C. and led to an era of mastery of construction materials that produced buildings of unsurpassed purity and lightness.

Purity because the Greeks used large blocks without mortar along the joints and without rendering. The blocks were linked by cramps and joggles of wood or metal (Fig. 25, 26).

Lightness as exemplified by the stoas with their long rows of columns (Fig. 27) producing concentrated loads carried by orthostats.

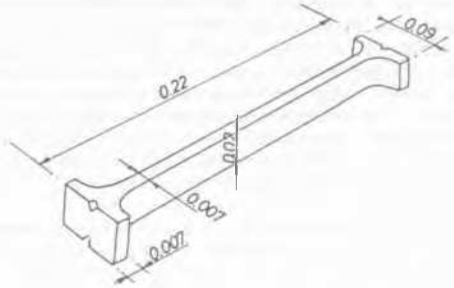


Fig. 25 - An iron cramp, the basis of Greek Architecture in reinforced stone.

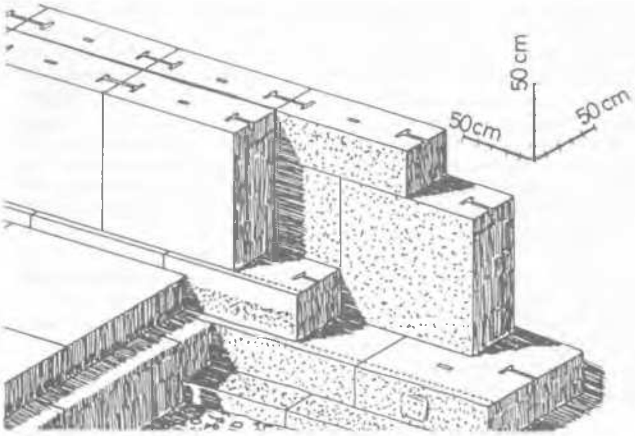


Fig. 26 - Orthostats in the temple of the Athenians (at Delos) with metal joggles.

Fig. 27 - Reconstruction of the Attilus stoa in Athens (Perm. of the American School of Athens).

These were long blocks of stone that were laid on their side, built up in two or three layers to form the upper part of the foundation. They had been used previously by the Hittites in the palace of Yarimlin in Anatolia (2nd millennium B.C.). One of the difficulties associated with a style of architecture that uses colonnades and porticos is that the concentrated loads in the columns can lead to differential settlements. The orthostats serve to spread out the loads to produce a uniform bearing pressure. This provides an interesting example of soil mechanics contributing to beauty in architecture.

For the case of a building that was founded on strip footings in a trench that had been cut and levelled and where the ground was hard, or even of rock, obviously the orthostats would have been superfluous. However this was not generally the case.

For reasons of economy, and noticeably in Asia Minor, early in their history the Greeks usually founded their buildings on pad footings, rather than strips or rafts, as found for example at Delos (Fig. 28).

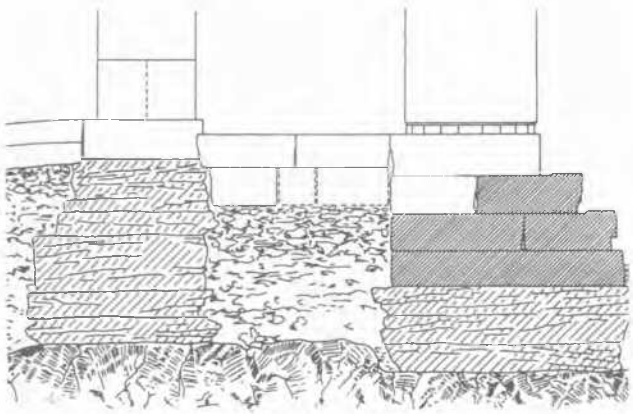


Fig. 28 - Ancient Greek isolated footings at Delos.

However structures built in reinforced stone using cramps are sensitive to differential settlements which explains why certain authors not only made references to foundations, temelia (θεμελια), but also to the reinforcement of foundations (R. Martin - 1965, note 4, p. 308).

The foundation technique using strip footings and orthostats became the most common type and with some rare exceptions (rafts) was adopted for most soils conditions. The dimensions of the trench were selected following certain rules, and details of some of these have survived. The excavations were then backfilled with a variety of materials (a layer of limestone gravel 0.2 m thick for the Heraeum at Samos where the trenches were up to 2.6 m deep; the same arrangement at Olympus for the buildings dedicated to Attis; a mixture of earth and shaped stone blocks beneath the walls of the treasures of Sicyon and Epidamne, a mixture of shaped blocks and broken stones beneath much of the Agora at Athens including the first temple of Apollo, from the 6th century B.C., the second temple of Apollo, from the 4th century B.C., and the tholos of the temple of Ares which dates from 470 B.C. Between this material and the orthostats would be a layer of second-grade shaped stone blocks, usually without mortar). As a general rule the Greeks took greater came over what could be seen, rather than what could not, and blocks for the foundations were usually of an inferior stone and less carefully shaped. Thus the role of the orthostats spreading out the load was all the more important.

The orthostats became more noticeable when the Greeks started to decorate them. Thus at the beginning of the 2nd century B.C., under Eumenes II, the acropolis at Pergamum had a base of orthostats that included a frieze 2.28 m high and 120 m long which celebrated the legendary struggles between the gods and the giants.

Wherever the ground was marshy and moist the foundations would be built on a layer of earth with cinders and coal (as at Olbia) or occasionally on compacted clay (the temple at Locros) or even an a mixture of chalk and gravel, according to Plutarch.

Rafts

Only very rarely did the foundations cover the whole plan area of the building. However, rafts were used for some special cases such as the tholos of Marmaria at Delphi, founded in an area where landslides and earthquakes were frequent, and the mausoleum at Halicarnassus. This latter structure was founded on a raft built of several layers of quadrangular blocks each of thickness 0.3 m and reinforced by iron cramps. The lateral dimensions of the blocks varied from layer to layer but were related numerically so as to allow the cramps to link the blocks together along joints in the different layers (R. Ginouvès - 1956 - Quelques relations numériques dans la construction des fondations de temples grecs). The raft allowed for the weight of the structure itself and for the nature of the basement containing the burial chambers. Similarly the temple of Ares in Athens is supported by a raft comprising five layers of alternating stone blocks resting on a single layer 0.3 m thick of blocks placed in a clay matrix.

A similar arrangement, with slabs stacked in alternation, was used as the foundation of buttresses for retaining walls.

Imperial Rome

The Greeks invented the rounded vault in the 4th century B.C. and the Romans made great use of it. Roman architecture was more massive than Greek architecture which meant larger foundation loads. They benefited greatly from the experience of Greek builders and as we have seen a number of authors, of which the most important was Vitruvius, attempted to draw up a set of rules for the construction of good foundations.

<u>The advice of Vitruvius regarding shallow foundations</u>

In Book I Chap. VIII Vitruvius sets out the requirements of a good foundation: "Where possible the excavation should continue down to solid ground, and even in solid ground should continue to such a depth where the loads in the walls can be safely supported: the foundations should be constructed of the strongest materials available and their width should be greater than the width of the walls above ground level". Further on he states that "In the foundations... the two sides of the wall shall be linked together using ties and keys (wooden billets, etc...) in order to ensure a solidness that will last". The title of the third chapter of Book III is: "De fundationibus tam in locis solidis quam in congesticiis", that is Vitruvius porposes to set out the rules for foundations on either solid ground or fill. He states that the foundations should be in proportion to the size of the building and in this respect proposes that for columns supported on strip footings the load be transferred from the column to the foundation through a circular base of diameter one and a half times that of the column. Following Book I Chap. VIII, referenced above, these circular bases would rest on footings founding at a depth greater then the diameter of the base.

Clearly the purpose of these rules, although not stated in scientific terms, is to distribute the loads so as to produce the lowest even bearing pressure possible.

One should not be led to believe that Vitruvius limited himself to rules of a very general nature, as he stated that they should be modified to take into account the loads in the columns and the soil conditions.

In a style of architecture using porticos the Greek masters laid down certain principles to be followed regarding the proportions between the thickness of the entablature (lintel or beam) and the diameter of the columns; this is the principle behind the Doric and Ionic systems, and others. Vitruvius extended these ideas to include the dimensions of the foundations. In this way, therefore, geotechnical engineering contributes to the rules of order, with the drawback that no one can admire the harmony of what is underground, and this is indeed an ungratifying aspect of our profession.

In a general way, throughout his work (Book I: Chap. VI, Book II: Chap. I, Book III and Book VI: Chap. X), Vitruvius stresses the importance that the foundation possesses "firmitas".

In the same way as for the Greeks the Romans were of course limited in the possible span of the architrave by the strength of the stone used, and this in turn limited the loads in the columns. However the use of the barrel vault meant that the support points could be spaced further apart, leading to greater loads in the columns. To cope with the greater foundation loads the Roman architects were guided by the following two principles set down by Vitruvius in Chap. III of Book III:

1) For their contact with the soil footings between column bases should have the form of a vault concave towards the sky,

2) If the soil is not firm (fill), it should be made firm by compacting it, using a machine for installing piles; in Chap. VII of Book VIII, he details his views on the compaction of soil for the base of a reservoir in suggesting the use of wooden piles reinforced with iron.

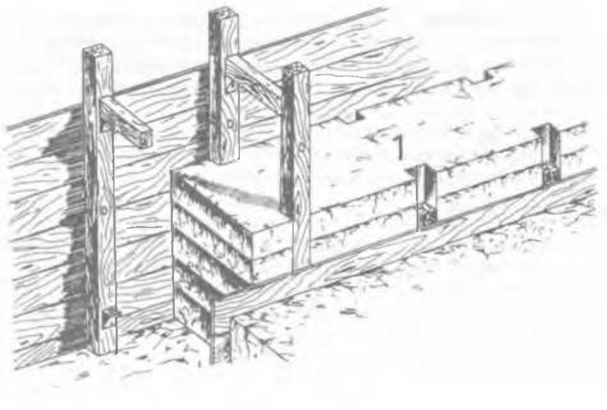
Thus, on the one hand, Vitruvius is the inventor of the idea of an inverted raft foundation, much used at a later stage particularly in Italy during the Renaissance, and also in the 18th century by Soufflot for the Panthéon in Paris, founded on the site of a former quarry; on the other hand Vitruvius was a keen advocate of compaction, which had proven to be a problem from the very earliest times: in this case rather than being by means of the feet of a man or animal it was, in its way, a form of dynamic compaction.

Originally the Romans used sun-baked bricks for the construction of shallow foundations, and later fired bricks (figlinae). The bricks became standardised to dimensions of 0.444 x 0.296 x 0.148 m. However, when the Tiber flooded in 54 B.C. erosion of the bricks in the foundations led to the collapse of many buildings and an edict banning this form of construction was issued (Vitruvius II 818 and Pliny XXXV 49). Nevertheless these bricks continued to be used in foundations for a while afterwards, although wooden reinforcement (armatura lignea) was included which strengthened the foundation as a whole and, as held by some authors of that time, made the buildings less easy to destroy by enemy war machines. The blocks of earth were fired in a wooden mould and became standardised as slabs of dimensions two Roman feet by one and a half.

All the same the edict was not always obeyed, and if we are to believe Seneca (4 B.C. to 65 A.D.), whose writings were not always wholly consistent, the collapse of one's house is one of the common misfortunes that can befall one during one's life.

Soon, however, the Romans invented concrete. The word concreto comes from caedere, meaning to cut: having shaped the stone blocks in quarries in the hills above Rome for the construction of retaining structures, the idea came to the Romans to mix the chippings left behind with the pozzolanic sands of the region, and lime manufactured in the furnaces in the nearby limestone hills. Certainly the geographical situation was exceptional but this also illustrates how inventive the Romans were.

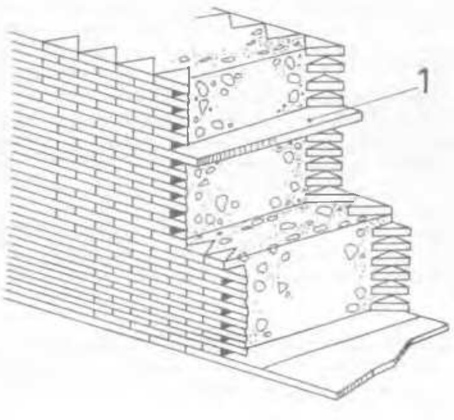
Initially concrete was used in wall foundations, and was cast inside a permanent brick formwork.



1 - Fired earth-slab.

Fig. 29 - Diagram illustrating the use of wooden reinforcement in foundations built of fired earth-slabs.

The concrete was never left exposed to the air, and if it was poured in any great thickness the centre of the mass would set rather slowly, which sometimes led to problems of settlement and loss of bond. Thus this new material was only rarely used other than in foundations.



1 Wooden tie-bar to withstand the concrete thrust .

Fig. 30 - Roman concrete cast inside brick formwork for foundations.

One of the major early successes of the use of concrete was in the raft of the Colosseum which was a circular slab 170 m in diameter. The Colosseum site was originally the location of the Domus Aurea Neromana lake, which was dug in order to collect the run off from three nearby hills, Celio, Esquilino and Palatino. it was possible to drain the lake through the Cloaca Maxima sewer, located at a distance of 500 m and at a level 11 m below that of the lake. The concrete could then be cast directly onto sound rock, a lithoid tuff.

The Romans were great builders and they used iron cramps to reinforce their structures, although to a lesser extent than the Greeks. Nevertheless they never came up with the idea of placing iron bars in concrete to overcome the problem of lack of strength in tension, no more than did the generations in the seventeen centuries that followed them. In this way there were sometimes difficulties associated with tension in concrete, even in foundations.

Such was the reason for the failure of the foundations of the Palace of Flavius, built on very variable fill material; similarly the partial failure of the foundations of the Pantheon in Rome, located on the difficult soils of the Campo Marzio. This latter structure was one of the very few in which concrete was used for the superstructure, albeit reinforced by arches of fired brick. The weight of the dome and the tambour were carried by a concrete ring beam foundation, wider than the tambow, but which cracked nevertheless. This required the construction of a number of buttresses to provide additional support.

The Mayas of Yucatan (around 200 B.C.) used raft foundations extensively for their buildings. These usually comprised a layer of large stones, of between 30 and 80 cm in size, laid on a prepared surface and covered by a further layer of smaller stones with lime mortar, forming a platform about one metre thick. This technique is not all that different from that used by the Romans at a later date for the concrete raft of the Colosseum.

In addition it is interesting to note in certain civilisations less advanced technically than the Romans that prefabrication played a role in the construction of foundations. Thus in New Mexico, the pueblo in the area near Chaco Canyon used stacks of stone discs 1 m in diameter as a support for columns. The same method appears in China for the support of wooden columns, in accordance with the Sung Code of 1103 A.D. The soil beneath the base was firstly carefully compacted, using a variety of manual methods some of which are shown in Fig. 31. The Sung Code provides a precise specification for compaction. On each square chi (1) of foundation two dans (2) of soil were laid; then two dans of stones or broken bricks were placed, followed by a further layer of soil, etc... Each layer of soil would be about 0.5 chi thick and would be reduced in thickness to 0.3 chi by six blows with a two-man weight; similarly the layer of stones or broken bricks would be reduced in thickness from 0.3 chi to 0.15 chi. Thus as early as the beginning of the 12th century the Chinese had drawn up certain rules for obtaining a maximum density.

We know that in Europe in the Middle Ages the monks assigned a secondary role to the secular sciences, so that the advice of Vitruvius fell into disuse. Thus it was that numerous buildings collapsed through lack of the "firmitas"

(1) One chi was about one third of a metre.
(2) Old Chinese unit of weight.

Fig. 31 - Sung Code of 1103. Site formation. The range of methods of compaction can be seen.

so cherished by Vitruvius. The foundations were hardly any larger than the elements of the structure supported and their dimensions were rarely chosen in relation to the loads to be supported but usually as a function of the space available and the shape of the walls and columns. Similarly insufficient care was taken in the choice of materials for the foundations. Even Bramante (1444 - 1514) who played such an important role in Italian architecture preferred to concentrate the available resources in the construction of the facade of a building rather than spend money vital to the strength of the foundations.

India

Let us finish this section by looking at the civilisation of ancient India, which we have already come across in the quotations from the Manasara . Many religious monuments were of ex vito origin and did not last long. A Buddhist stupa, which is a hemispherical structure derived from the tumulus, might have been built with a view to improving the lot of the owner in his future lives. It was not, therefore, designed for durability. Hence it is not surprising to find in the sections of the Manasara devoted to foundations, mixed in with a variety of incantations and poetry, recommendations related to the permeability of the soil and to density and compaction. For example:

Chap.V 18-19 "In an auspicious moment, karana (eleven divisions of the day) and lagna (conjunction), while the highly learned Brahmins keep pronouncing all auspicious benediction."

20-22 "In the selected spot the earth shall be dug over the whole of the plan area of the building. The hole shall be made quadrangular in shape and one cubit deep, and filled with water to the same level on four sides." (one cubit = 0.52 m)

31 "In the morning, the wise builder together with the architects should examine the condition of the water in the tank."

32-33 "If it is seen that there is some water left, the soil should be taken to be for good; if on the other hand it be entirely dried up, it means the loss of wealth and sustenance; and if it be wet, it means destruction."

These days we would prefer a permeable sandy material for the founding stratum in order to ensure an adequate bearing capacity.

34-35 "If the hole be filled again with the earth dug out, to the original level, the soil is fair; if it be not filled up with the same earth, the soil is bad; and if it be over-filled, the soil is good."

This is certainly more rational, but what about...

Chap. V -10 "Cows, oxen and calfs shall be brought."

11-14 "The herd shall compact the soil with their feet and with their breath."

15 "Decorated by the imprints of their feet, etc..."

With such an approach to the problem, the conclusion is hardly surprising!

Chap. IV - 38-39 "These being the rules anyone who is so stupid as to ignore them shall be accursed" .

3 - Foundations with very high bearing pressures

A great number of structures have not survived to the present day because the foundation bearing pressures were too great (pressures of 500 to 1000 kPa are not out of the ordinary); many others that are still standing are badly cracked, or are tilting, or have undergone large settlements. The factor which controls the total settlement, and hence the differential settlement, is the total load divided by the length of the perimeter of the foundation. Regardless of the shape of the perimeter or the stiffness of the foundation, the settlement is given approximately by four times this factor divided by the modulus of deformation of the soil (Kérisel - 1985), as confirmed by calculations using the formulae of Boussinesq.

In this regard it is interesting to compare the load concentration (expressed in MN per m of perimeter) for some famous old structures with those that are typical for some of the larger structures of today, as shown in Table III.

TABLE III

SOME INDICATIONS REGARDING THE LOAD CONCENTRATIONS BENEATH LARGE STRUCTURES ANCIENT AND MODERN

	Structure	Load Concentration (MN/m)	Ground Conditions	Settlement (mm)
ANCIENT	Pyramid of Cheops (Egypt)	70	Rock	
	Pyramid of "Tepenapa" (Mexico)	46	Rock	
	Pagoda of Phra Pathom Chedi (Thailand)	10	Soft Bangkok clay	2 500 (ave.)
	Dome of St. Paul's (London)	3.7	London clay	160 (ave.)
	St. Catherine's Tower (Hamburg)	3.1	5m peat	900 (diff.)
	Tower of Pisa	2.4	Clayey silt	{ 3 000 (ave.) { 1 800 (diff.)
	Towers of the Marienkirche (Lubeck)	2.2	Fine silty sand	
	Campanile of St. Mark's (Venice)	1.9	Soft alluvial soils	Collapse in 1902
	Towers of Lubeck Cathedral	1.3	Silt, clay and sand	450 (diff.)
	Tower of Suzhou (China)	1.25	Layer of clay	800 (diff.)
	Campanile of Burano (Italy)	0.5	Silt and clay	435 (diff.)
MODERN	Nuclear power stations	3 to 9		
	Large petroleum tanks	1 to 5		
	Large silos	1.5 to 4		
	50-storey building	4 to 5		

We can see that the greatest load concentration ever achieved is due to the Pharaoh Cheops, and dates back nearly 5 000 years. He was sensible enough to found the structure on rock. On the other hand there are a significant number of ancient structures for which the load concentration exceeds 1 MN/m and which are founded on compressible soils with a corresponding low modulus of deformation. This has led to large settlements, which for some structures are still continuing, as shown in Table IV. The case of the Buddhist monument of Phra Pathom Chedi (Brand 1981) is little known. This structure weighs no less than 5 000 MN and has a circular base 158 m in diameter, founded on soft Bangkok clay. It was constructed in three stages, with the first stage begun around 300 B.C. (Fig. 32). It has settled fairly uniformly a total of about 2.5 m.

Table IV is a very limited list of structures that have tilted significantly, and does not include a large number of structures, dating from the distant past, that are no longer standing. Notable among these are religious monuments of the Middle Ages such as the towers of Ramsey Abbey (985 A.D.), of Gloucester (11th century) and of Worcester (1175 A.D.), and the lantern turrets which, from the 14th century onwards, were a common feature of cathedrals, located at the intersection of the transept and the choir.

These towers and lantern turrets, and later domes, led to very high load concentrations (see Table III, the dome of St. Paul's (1)), often resulting in collapse of the structure or to large differential settlements between the element in question and the remainder of the building.

(1) 700 MN for a circular perimeter 60 m in diameter. Lord (1974).

TABLE IV

SOME TILTS OF OLD STRUCTURES

Structure	Height (m)	Base Dims (m)	Tilt	Current Rate secs/yr	Remarks
Tower of Pisa (1173-1370)	60	ø20	10	7	
Bell tower of St. Moritz	34	5.7 x 5.7	9.5	24	After two unsuccessful attempts at stabilisation (Huder 1981)
Al-Habda Mossoul minaret, Iraq (11th century)			9	0	Underpinned with root piles (Lizzi 1981). Increase in tilt of 10% during remedial works, then stabilised.
Garisenda Tower Bologna (1109-1119)	48	7.44 x 7.44	6.7		
Campanile of Burano Venice (16th century)	53	7.5 x 7.5	6.2	0	Underpinned with root piles (Lizzi 1981). Increase in tilt during remedial works, then stabilised.
St. Catherine's tower Hamburg (13th century to 1656)	66	14 x 15	6.0	0	Underpinned in 1968 (Pieper 1983)
Tower of Suzhou (959)	47	Octag. of side 5.2	4.9	24	
New tower of Saragossa (1504-1512)	56	Octag. of side 3.15	4.6		Demolished in 1892
Towers of the Marienkirche Lubeck	60	19.6 x 19.6	3.9	0	Restored after the 1939-45 war.
Towers of Lubeck Cathedral (13th century)	50	15 x 15	3.8	0	Stabilised using inclined piles. (Smoltczyk 1981)
Asinelli tower Bologna	97	9 x 9	2.7	6.5	
Ghirlandina tower Modena (1224-1319)	88	10.6 x 10.6	2.6		
Campanile of St. Mark's Venice	98		0.8		Collapsed 14/7/1902.

Further details concerning some of these monuments are included in Annex II.

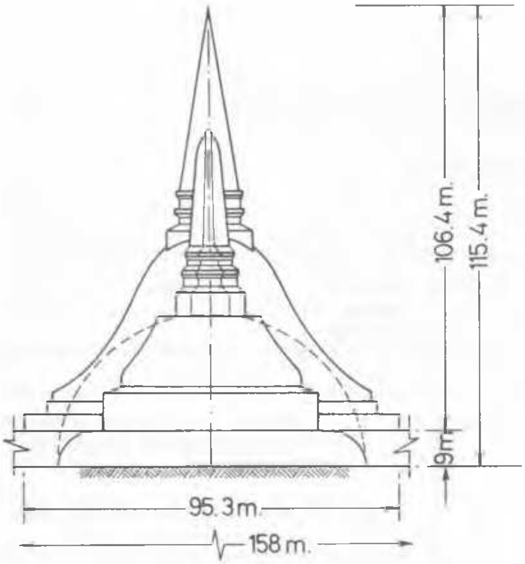


Fig. 32 - The three stages of construction of the pagoda of Phra Pathom Chedi (Thailand) - Brand (1981).

Fig. 33 - The new tower of Saragossa, demolished in 1892 because ... it cast too much shade onto the shops (after an engraving by Roberts).

Things were not necessarily any better during the Renaissance. Of 200 campaniles and towers in Bologna, only 30 remain; the pattern is similar in Venice. As for Spain, Ortiz (1984) provides an impressive list of towers that no longer exist.

Of course not all the towers that have disappeared have done so through being badly founded. In particular the tower of Saragossa (Table IV) had perfectly good foundations. This structure comprised 1 100 courses of rough-cast mortared bricks. The tilt of the tower (Fig. 33) can be explained by the plasticity of the mortar, that it set more quickly on the side exposed to the sun (Gaya Nuno - 1961), and, probably, the variation in the thicknesses of the mortar joints. The decision to demolish the tower in 1892 was influenced by the wishes of the town's powerful merchants, because ... it cast too much shade onto their shop fronts. Other towers, such as the Campanile of St. Mark's (Cestelli Guidi 1975), have collapsed through a combination of faults in the structure itself and inadequate foundations. The courses of mortar in the structure were too thick and the mortar too plastic, which led to cracking in the stonework and a redistribution of the bearing stresses: for the reconstruction of this campanile the perimeter of the foundations was increased by 80%. Rather the opposite applies to the Tower of Pisa which, despite inadequate foundations, is still standing thanks to the superior nature of the stone and the high quality of the jointing.

As so many towers have collapsed or have been severely deformed, it is not surprising that a number of legends have grown up around them, some amusing and others rather macabre. Let me digress a moment with two such stories.

It is believed that the tower of Terlan, in Tyrol, leant over to watch a young virgin passing by; it is still leaning over on the off chance that one day it might see another.

A Balkan ballad tells us of the building of a tower at Shkoder (Scutari in Italian), a town in Albania, an old religious centre located at the outlet of a lake surrounded by marshes. The story is told by M Yourcenar (1981):

Fig. 34 - The obelisk at Axum which was broken in its fall.

"Three brothers were building a watchtower ... but each time that they got to the point of being able to place a bunch of herbs on the roof, the wind got up in the night and the demons came down from the mountains and they pulled it down, as God did the tower of Babel. Now there are many possible explanations for why a tower should collapse, such as the lack of skill of the builders, insufficient strength of the supporting ground, or inferior mortar in the joints. But for the local peasants, the Serbs, the Albanians and the Bulgarians, the cause of the disaster was clear: that no such structure would stay standing unless a man or a woman had been incarcerated in the foundations, their skeleton supporting the heavy flesh of stones until Judgement Day. At Arla in Greece there is a bridge and beneath the water you can see a lock of hair of a young girl that sticks out of a crack and wafts in the water like a blonde plant".

This section covers not only towers, lantern turrets, minarets, campaniles, but also pagodas, obelisks, lighthouses, ancient silos, stupas, pyramids etc ...

Unfortunately only very rarely have the archaeologists provided sufficient detailed information on the foundations of these monuments. For example, at Axum, formerly a holy city and the centre of the Abyssinian kingdom, one can see the remains (Fig. 34) of a 34 m high obelisk, that would have been the tallest in the world (1). It marks the tomb of a king who lived before Christ. The cross section is square 2 m x 2 m, giving a pressure at the base of 825 kPa. The data from the archaeological dig are insufficiently detailed (Leclant 1959) to tell us the dimensions of the block of stone that supported the monument or to show whether the obelisk fell due to inadequate foundations, or, as held by some

(1) The tallest obelisk in Egypt belongs to the reign of the queen Hatchepsout, at Karnak, and is 29.50 m high. The unfinished obelisk in the quarry at Aswan would have measured 41.75 m.

historians, was overturned by the Jewish queen Judith who wreaked havoc in the area in the 10th century.

Nevertheless it is certain that many obelisks did have inadequate foundations (see comments by S. Clarke, R. Engelbach 1930). The same applies to many of those that were transported to Rome, if we are to believe Pliny the elder (Book XXXVI): under the reign of Augustus the obelisk erected in the Campo Marzio was made into a sun dial, with marble paving around the base. Within 30 years the sun dial had become hopelessly inaccurate: in the 18th century the obelisk was removed and re-erected in the Piazza Montecitorio where it may be seen today.

However the only monuments which are really of interest are those for which sufficient details of the geometry, the loads and the soil conditions are known. Unfortunately for some structures it might be dangerous to carry out any site investigation holes close to the structure: we know for example that the rate of tilt of the Tower of Pisa increases when any drillholes are undertaken close by.

For this reason we will only look at a few typical examples; two towers, a pagoda and some pyramids, for which sufficient information is available to make a study worthwhile.

The Tower of Pisa

Many of our colleagues (K. Terzaghi, A. W. Skempton, E. Schultze, G. A. Leonards, J. K. Mitchell, T. W. Lambe, A. Croce, G. Calabresi, G. Viggiani, etc ...) have studied the problem of the famous leaning tower. As remarked by A. Croce during the symposium on the Interdisciplinary Approach of the Human and Physical Sciences, held in Naples on the 9th and 10th April 1984, and organised by him, this monument is a part of the world's cultural heritage. (Fig. 35).

A large number of groups have come in turn to Pisa to analyse the tower; an international competition was begun in 1972 with a view to deciding upon the means of stabilising the structure; but up until now no decision has been taken on the remedial measures, despite a large number of proposals. Nevertheless the competition has, at least, produced three superb albums which provide an excellent summary of the history of this monument (Richerche e studi su la Torre Pendente di Pisa 1971 - Firenze - Istituto Geografico Militare). The construction of the tower began in 1173 at a time when the Republic of Pisa was flourishing. In fact it has leant in a variety of directions and in three stages, separated by two gaps of one hundred years each, it tilted successively to the east, the north, the west, and finally the south, while at the same time effectively screwing itself 3 m into the ground.

Fig. 35 - The tower of Pisa (1984). Photograph taken on the occasion of the Congress of Naples 1984.

The structure weighs 15 700 tons and rests on a circular base 20 m in diameter. The underlying soils are sandy silty alluvial deposits, but include lenses of clay which on the south side are overconsolidated. In this way the structure now leans, and has for several centuries, in the direction SSSW. The tilt has reached almost one in ten, being more exactly 18 330 seconds of arc; since the beginning of the century the rate of rotation has gone through three stages of being nearly constant, passing successively from 5 seconds per year, through 14, to the present rate of about 7 seconds per year (Fig. 36). This is despite the ban on pumping in the area, which has resulted in the phreatic surface being restored to its original level. The structure has now stopped settling, and in fact the latest measurements have shown that relative to the tower it is the surrounding ground which is moving, in tilting from the NE towards the SW. In the past it was possible to see that as the tilt of the tower increased, and with it the overturning movement, the settlement of the structure also increased and hence the built in depth and the resisting moment, resulting in a constant rate of rotation. Now, however, the overturning moment continues to increase while there is no corresponding increase in the built in depth: in fact the surrounding ground is tending to follow the rotation of the tower.

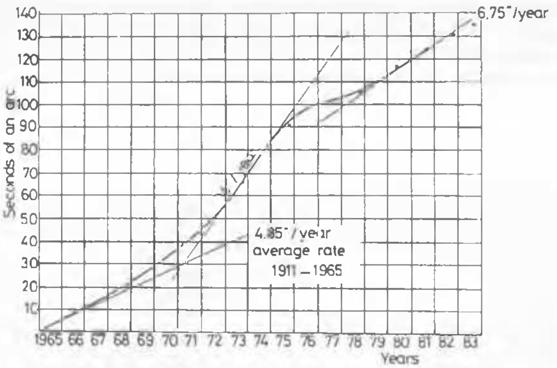


Fig. 36 - Rotation of the Tower of Pisa over the past 20 years.

Following the unsuccesful competition, another Italian commission has been set up. Let us hope that their work results in a decision.

Clearly this is a difficult problem and it must be borne in mind that other such attempts at stabilisation have frequently been unsuccessful, or have only succeeded in halting the movements at the expense of a sharp increase in the tilt during the remedial works. Nevertheless the situation at Pisa is certainly not improving. It calls to mind two Latin words that are particularly apt in this context: impendet imminet, which desribe a threatening overhang.

The Pagoda Tower of Suzhou
(Wen-Xi Yuang 1981)

Built around 960 B.C. this tower is 47m high and weighs 5 000 t. The base is octagonal, of side 5.20 m and the underlying soil is a soft to firm clay overlying a sloping rock face, such that on one side the clay is 2.60 m thick, while on the other side, towards which the tower tilts, the clay is 5.80 m thick.

As shown in Table IV the tilt is about 4.9 %, which is considerably less than the tilt of several other structures still standing, but the rate of increase is 24 seconds per year which is nearly four times that for the Tower of Pisa. The seventh storey of the tower was rebuilt in 1638, so that the change in tilt since that time can be measured. In China it is felt that stabilisation measures for this structure are required urgently.

The Pagoda of Longhua

The pagoda originated in India and was introduced to China with the arrival of the Buddhist religion, during the Eastern Han dynasty (68 A.D.). There are many thousand pagodas in China, of a wide variety of shapes. However little is known regarding the foundations of these structures. The

Fig. 37 - Tower of Suzhou.

Fig. 38 - Pagoda of Longhua.

pagoda of Longhua is exceptional in this respect (Fig. 38). This structure dates from 977 A.D., from the Sung dynasty, which is well known for its construction achievements. It is octahedral and reaches a height of 40.4 m. The underlying soil is alluvium extending to a depth of 30 m and comprising silts and soft clays. The allowable bearing pressure for such a soil, following the recommendations of the China Civil Engineering Society, would be about 80 kPa, and there are a large number of structures founded on similar material, for which the applied bearing pressure exceeds this value, which have either collapsed or become severely distorted. It is not clear, therefore, why this structure is still standing and undamaged.

Around 1950 an investigation of the foundations was undertaken (1). This revealed that the brick base of the structure is supported on a wooden raft which in turn rests on wooden piles at very close spacing. The piles are of section 14 x 18 cm, spaced such that the gap between faces is only some 8 to 10 cm. The complete layout of the piles and their lengths are unknown. Nevertheless it is clear that what has been discovered here is one of the first piled raft foundations ever built, completed over 200 years before construction of the Tower of Pisa began.

The Pyramids of Egypt

The Pyramids pose questions not only to archaeologists, philologists and geographers, but also to geotechnical engineers where problems arise in three particular areas:

- foundations
- slope stability (section III-5)
- "underground" openings (burial chambers - see section IX)

Five of the most important pyramids are, chronologically, those of Saqqarah, Meidum, Dahshur South and North, and Cheops, and were built over a period of less than a century, beginning around 2750 B.C. Saqqarah (Fig. 39) marks the abrupt transition from the use of mud bricks for construction of ziggurats, which eroded with time, to the use of stone for building structures that have lasted nearly five thousand years. The pyramid comprises six tiers, with an average side slope of 52° to the horizontal. The stability of such a steep face is assured by the ingenious structure of the pyramid, devised by the reknowned architect Imhotep. The tiers are built around a central core of square cross section, decreasing towards the summit: the tiers are made up of boxes of rectangular section, 2.50 m thick, which were faced with Tura limestone but were infilled

Fig. 39 - The Stepped Pyramid of Saqqarah (70 m high).

Fig. 40 - Model of the arrangement of blocks used in a step pyramid - L. Kérisel.

(1) This information was kindly supplied by the Museum of Shanghai, following a request from Zhao-Jun.

with locally quarried stone (1). These boxes are sloped backwards at an angle of 72° to the horizontal (Fig. 40) so that the earth pressures are directed towards the toe of the wall (See Annex III) where the resultant forces are transferred to the underlying rock.

Besides acting as retaining walls the blocks perform the rôle of internal buttresses to the strucure, although until now this double function does not appear to have been recognised.

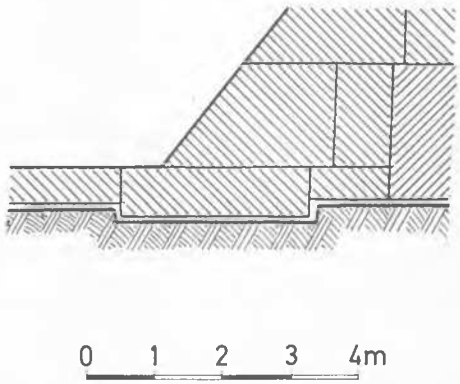


Fig. 41 - Toe-in to rock providing horizontal restraint: the great Pyramid of Cheops (after Borchardt).

Imhotep was probably aware of the problems of tangential forces acting on the base of the great ziggurats built in Mesopotamia a few centuries beforehand, and wisely built the pyramid at Saqqarah on rock, toed-in at the base. The site is on the west bank of the Nile, on the edge of the Libyan desert. The same detail of toeing-in at the base was used by Huni at Meidum, and Cheops for the Great Pyramid (Fig. 41). Unfortunately the southern pyramid at Dahshur, probably belonging to Snefrou, was less wisely sited, being founded on stiff clay. This, or the pyramid at Meidum, would have been the first attempt to build a true pyramid, that is one having straight sides, rather than being built in steps. It appears that it was originally intended that the angle to the horizontal of the faces would be 60°: this pyramid contains two descending corridors, one near the base in the north face and one higher up in the west face, and in each of these it is possible to find the original side slope which follows the line AC (Fig. 42) and intersects the base at a distance of 15.60 m from the toe of the final face.

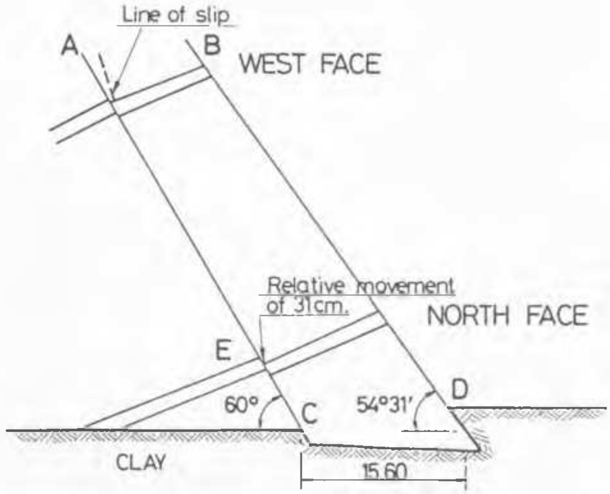


Fig. 42 - Successive stages in the construction of the Bent Pyramid at Dahshur. Differential movement between the new face at 54° 30' and the original face at 60°.

It appears most likely that the load concentration from the original steep-sided pyramid led to some form of collapse which persuaded Snefrou to reduce the side slopes. Nevertheless this was not entirely successful either since, due to the inadequate bearing capacity of the underlying soil, the wedge ABCD (Fig. 42) subsequently moved significantly relative to the rest of the structure. The relative movement measured in the northern descending corridor is about 23 cm, and in the western descending corridor the movement is about 8 cm. This would explain why, having reached a height of 49 m (Fig. 43), it was decided to flatten the rest of the pyramid to an angle of 43° 30', giving the structure its unique shape: hence the name the Bent Pyramid. However, significant cracks appeared in the burial chamber and in the western descending corridor, which is probably why Snefrou abandoned his original choice of final resting place and commissioned

(1) Due to the irregular nature of the annual flood, the Egyptians took the precaution of building grain silos and, following a good harvest, no doubt had come to an appreciation of the lateral loading on the silo walls applied by a granular material.

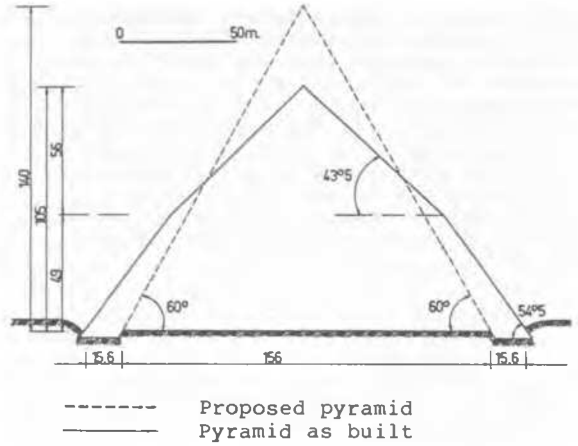


Fig. 43 - Section through the Bent Pyramid (Dahshur South).

another pyramid just to the north, the North Stone Pyramid. This is a true pyramid and is founded on rock. It is more modest in size and the faces slope at the relatively shallow angle of 43° 30'.

The Great Pyramid of Cheops has a square base of side 212 m, and the faces slope up at an angle of 52° 30' to the horizontal. We have alrady seen the device used to resist tangential forces along the base. The stone courses are slightly dished (as shown in Fig. 44) and some people believe that this is another example of a technique deliberately employed to improve the stability of the structure (Mendelssohn (1944)). However a calculation assuming elasticity of the substratum shows that the expected settlement profile is of the same form as the curvature observed: indeed this would be a possible method of deriving a modulus of elasticity of the underlying rock.

4 - Foundations subjected to an overturning moment

As religious architecture developed through different ages so the spaces between columns increased as well as the overturning moments carried by the foundations. The Egyptian hypostyle temples had their columns closely spaced. The Roman barrel vault produced spans of 12 m, while column spacing in the airy Gothic cathedrals might be some 16 m. The maximum bearing pressures beneath the outer face of the foundations often exceeded values that we would consider acceptable today.

Whereas the severe deformation of Santa Maria la Real del Sar, in Spain, (Fig. 45) may be attributed to inadequate foundations for the overturning moments acting, this is certainly not the only possible mode of failure for such buildings. It has been shown (Kérisel 1975) that the collapses of the two structures with the largest spans from the Romanesque and Gothic periods,

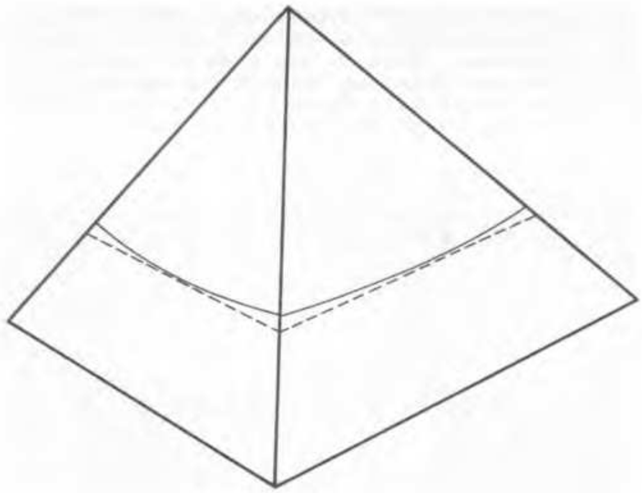


Fig. 44 - Differential settlement of the Great Pyramid of Cheops, due to the high bearing pressures.

respectively Cluny III with a 29.50 m span and Beauvais with a 48 m span, were not due to poor foundations but to structural defects.

The cause of failure may be attributed to the fact that the thrust from the roof was transferred to the columns at too high a level, and that the materials used for construction of the columns were unsuitable. Thus the facing stone was of good quality and the joints were thin: however, the core comprised rough-cut blocks set in a relatively compressible mortar. The modulus of elasticity of dressed stone with thin joints, may be taken as about 80% of that of the stone itself, regardless of the quality of the mortar, but this figure drops to about 20% for rough-cut blocks set in a mortar made with lime that is too old. For this reason the bending moment and axial force in the columns were carried mostly by the stone facing, leading to failure. Other failures may similarly be related to the compressibility of the mortar leading to stresses being concentrated along the line of greatest resistance, that is where there is stone. This recalls a recent paper (Barton et al. - 1978) in which it was shown that the inter-particle contact stresses in a granular material can be as great as 2 000 times the average stress acting on a section.

Strangely, though, it appears that the causes of failure were not appreciated, so that suitable changes, such as increasing the thickness of the facing blocks, were not undertaken. A technique invented by the Mayas of driving stone wedges into the mortar and stone mixture could have reduced the compressibility of the cores of the columns. The same mistake was repeated much later in the construction of the Panthéon in Paris, which threatened to collapse at the time of

Fig. 45 - Santa Maria la Real del Sar - overturning.

Fig. 46 - The basilica of Vézelay - Distortion of the vaults and pillars.

the Revolution (Kérisel 1983). Even a short time after a failure we find mistakes being repeated, particularly in the 12th century during the transition from Romanesque to Gothic architecture: Cluny III collapsed in 1123; construction of the church at Vézelay in the Burgundy district began in 1096, and it is clear that insufficient measures were taken to carry the thrust from the vaults. As at Cluny this structure was taller and less massive than the churches of the 11th century, although the beautiful arches built in alternate layers of white and grey-green stone reached no higher than 22 m; the vaulted roof supported by these arches heard St. Bernard preach the crusade in 1146 and Thomas Becket threaten Henry II with damnation if he did not repent; it saw Philippe-Auguste and Richard the Lionheart when they met in 1172 before embarking for the Holy Land. However it was in need of strengthening; the flying buttresses were not added until 1840, by Viollet le Duc, when the nave was believed close to collapse.

The Byzantine cathedral Hagia Sophia in Istanbul deserves a special mention for the way in which the thrust from the dome was taken out, using vaults rather than buttresses (A. Choisy - 1883). The desigr turned out to be rather ambitious for with the first earthquake the dome, which was too flat, collapsed and had to be rebuilt with a more rounded shape in order to reduce the horizontal forces. This led to additional settlement and deformations.

One of the most interesting religious structures is York Minster (Fig. 47) not only because of the extensive ground investigations carried out there, but also because of the variety of geotechnical problems that have arisen, including collapse of the main tower, walls overturning, and differential settlements due either to high load concentrations or to the presence of preconsolidated areas from an older structure.

The main tower collapsed in the 13th century and unfortunately some of the columns for the new tower were founded on the remains of the walls of the original Norman church which has led to differential

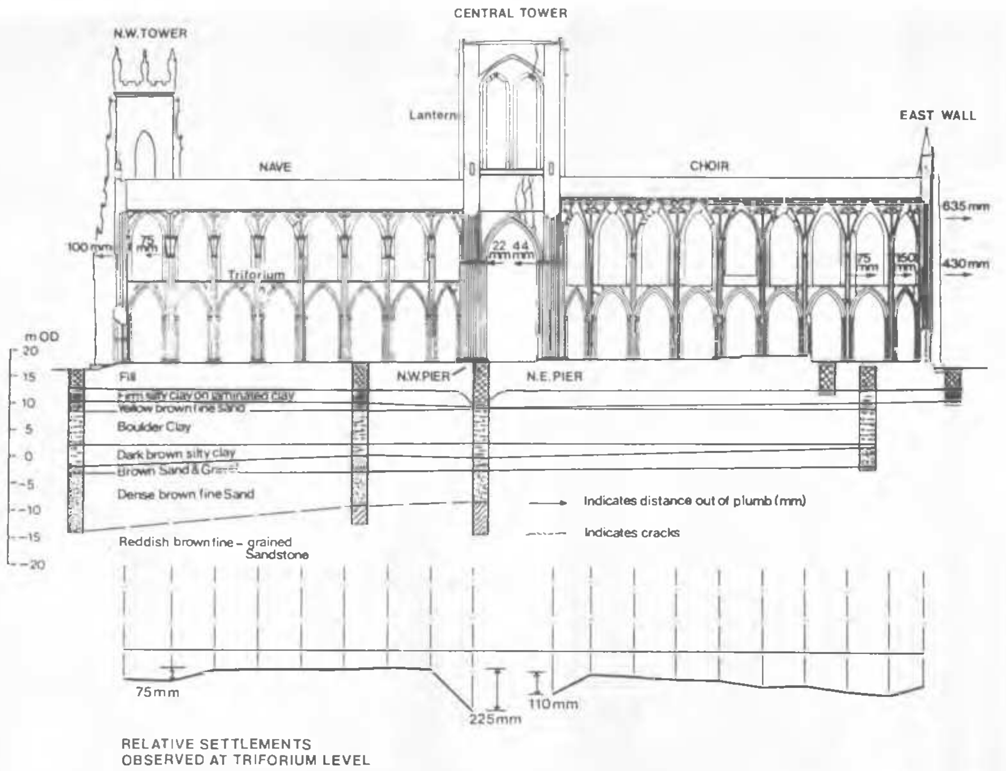


Fig. 47 - York Minster. Section through the nave and choir showing the soil strata and horizontal movements of the structure - J. A. Lord 1981.

settlements between columns. In addition the tower has settled relative to the rest of the church (Fig. 48), due to the high load concentration.

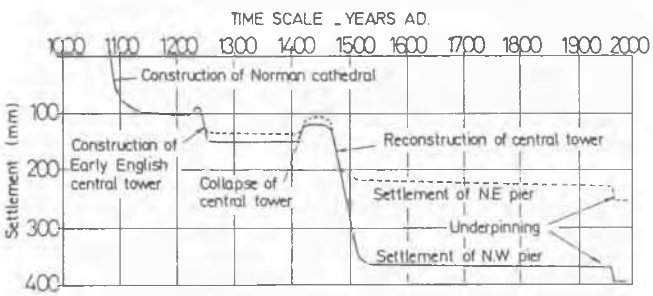


Fig. 48 - Inferred settlement - time curve since 1080 - J. A. Lord 1981.

The philosopher Alain has referred to architecture as "art at rest". As we have seen this is not always true for old structures: some adapt to the movements while others yield. Restoration work freezes the structure at a moment in its life.

5 - Foundations on natural slopes and the stability of man-made slopes

1 - Foundations on natural slopes

Natural slopes on which man has built may become unstable due not only to the weight of the structure but also to other changes caused by the presence of man, such as an alteration in the groundwater-flow regime.

However a slow steady creep of the hillside may not be affected by man's presence. We will look here at a few interesting cases of buildings founded on slopes: this is not the place for an in-depth discourse on the stability of natural slopes, neither for a catalogue of all the old towns, castles, dungeons or high walls built on steep slopes that are showing signs of instability (of which we may cite Orvieto and San Leo in Italy (Diamanti 1981), Villacarillo, Alcala la Real in Spain (Ortiz 1984), Peiden in Switzerland (Haefeli 1967), St. Moritz (Huder 1981), Herrenberg in Germany (Wenzel 1981), etc .) The cases of Peiden and St. Moritz typify the problem of a structure founded on a natural slope creeping at a steady rate (in the case of Peiden, the rate is 22.8 cm per year).

The bell tower at St. Moritz (Fig. 49) - see Table IV - has undergone translation as well as rotation (Fig. 50). An unsuccessful attempt at stabilising the structure was made in 1928 by building a large buttress at the toe (Fig. 49). A second attempt was made in 1978 by anchoring the wall (Fig. 49). This has only been partially successful, however, as the fixed lengths are in a zone that is itself subject to movement.

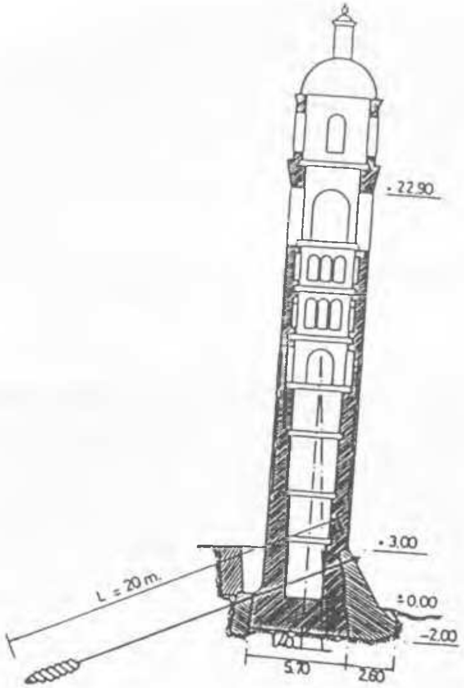


Fig. 49 - The bell tower at St. Moritz, founded on an unstable slope (Huder 1981).

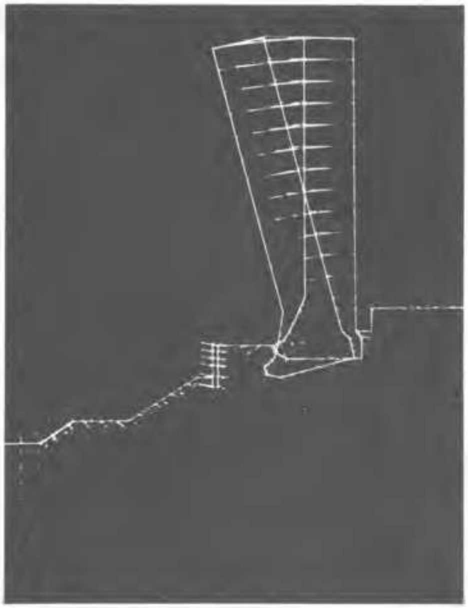


Fig. 50 - St. Moritz - finite element study of the rotation of the tower and the creep of the slope - (Huder 1981).

Of the numerous other examples of this problem we shall look at two that are particularly spectacular: the temple of Borobudur and the abbey on the Mont St. Michel.

The Temple of Borobudur

The largest temple dedicated to Buddha is that of Borobudur in Java, which dates from around 800 A.D. It comprises a vast series of terraces and retaining walls (Figs. 51 and 52) that mask a hill comprising clay overlying tuff. The terraces are symbolic: the pilgrim passes from the sphere of worldly desires, to which he is a slave, through the sphere of forms, where he has conquered his desires but retains his name and body, to reach the sphere of liberation where, having freed himself from all ties with the world, he may attain nirvana.

The wall representing the sphere of worldy desires, at the foot of the terraces, includes some 160 relief sculptures, but these have been covered up by a thick stone wall of volume 13 000 m^3. Rather than being for the purpose of hiding the lurid pictures from the pilgrims, it is probable that the wall was built at a period when the complex of terraces was showing signs of instability, perhaps even during construction of the monument.

The climate at Borobudur is hot, and during the monsoon extremely wet; a minimum of 2 000 mm of rain falls between October and March, the majority of which is concentrated in a few downpours. This leads to a build up of pore-water pressures behind the retaining walls, particularly at the toe.

Following an unsuccessful attempt at the beginning of the century the monument has, with the financial and technical assistance of UNESCO, recently been completely restored, at a cost of $20 million. This is one of the most important restoration projects ever undertaken, and has involved the collaboration of geotechnical engineers, architects, hydraulic engineers, climatologists, etc ... Let us recognise the outstanding success of this inter-disclipinary effort to preserve one of the most important monuments of the world's cultural heritage.

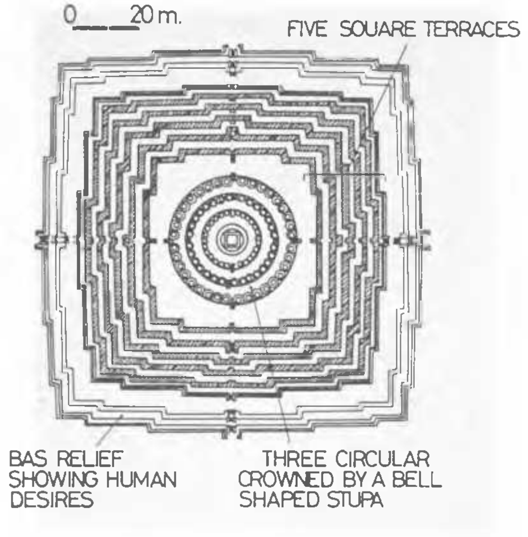


Fig. 51 - Plan view of Borobudur.

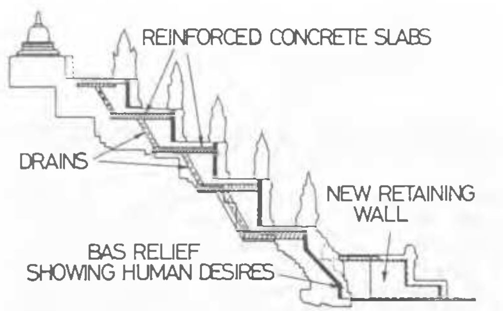


Fig. 52 - Section through the terraces at Borobudur, after the restoration.

It was hoped at one time to remove the wall at the toe and hence to uncover the relief sculptures of the sphere of desires. However the cost of undertaking the work without in any way endangering the stability of the monument proved prohibitive. The restoration works involved dismantling the square terraces stone by stone (Jayaputra 1984) in order to cast reinforced concrete slabs. Surface drains and lead sheeting were installed to channel the run off. Some 240 000 carved stone blocks, forming the outer surface of the monument, were numbered, cleaned, brushed and treated with chemical pastes to remove all organic matter.

The mortars used were of bituminous araldite mixed with sand to provide a material that is sufficiently flexible to accommodate movements due to earthquakes, which are frequent in this area.

Heavy structures founded on slopes : Mont St. Michel

Religious buildings have frequently been founded in precarious locations on steep slopes. One of the most striking examples is the abbey at the summit of the Mont St. Michel, a rocky outcrop (comprising feldspathic granite and granulite, quartz and tourmaline) that rises some 100 m above the surrounding bay, located at the corner where Brittany and Normandy meet, where the tidal range is one of the greatest in the world.

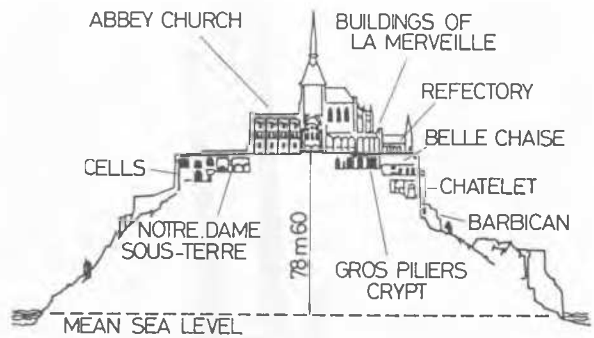


Fig. 53 - Mont St. Michel
East-west cross section.

In the 10th century there was a Carolingian church near the summit (now Notre-Dame sous Terre, see Fig. 53). This was later razed and the basement was used as a foundation for an abbey built during the 11th century. The abbey is irregular in shape as a result of the nature of the terrain (P. Gout - 1910). The roof of the nave was of wood and covered with panelling, as was the case for all the churches in the region prior to the 12th century, and was struck by lightning and burnt down several times. The roof was later replaced by stone vaulting which involved a certain amount of modification and adjustment as the builders of that period were inexperienced in this form of construction for such great heights. However this led to an increase in the loads acting on the foundations, particularly on the old Carolingian pillars. At the same time the vaults of the side aisles became distorted because the buttresses founded on the crest of the slope were insufficiently large. Eventually on the night of the Saturday before Easter 1103 the northern part of the nave gave way, only eighteen years after its completion. Rebuilt in the Romanesque style, it is still standing. In 1421 it was the choir which collapsed down to ground level where it was supported on a Norman crypt.

The Romanesque builders were succeeded by their much more able Gothic counterparts who knew how to lighten the thrust from the vaults and to direct it to regularly spaced buttresses more securely founded in the slope. It is to them that we owe the two buildings that make up La Merveille, built on the North side, and facing East, between 1203 and 1228 (Figs. 54 and 55), also the elaborate Gothic choir founded on the new Crypte des Gros Piliers (Figs. 55 and 56) which perches on the edge of the hillside. Beyond this the array of flying buttresses appears as if an extension of the hillside itself.

In its final form the abbey on the Mont St. Michel is a remarkable example of

Fig. 54 - Buttresses of La Merveille.

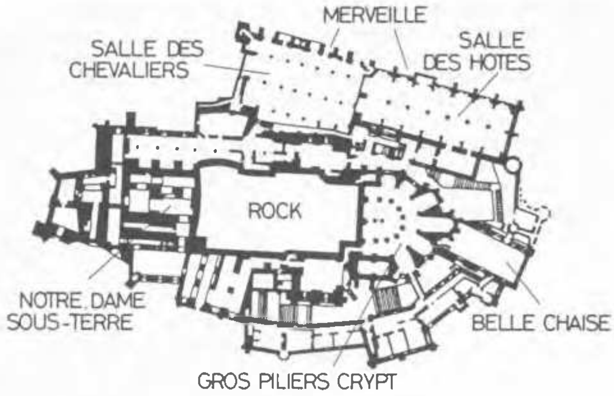


Fig. 55 - Mont St. Michel - Intermediate level.

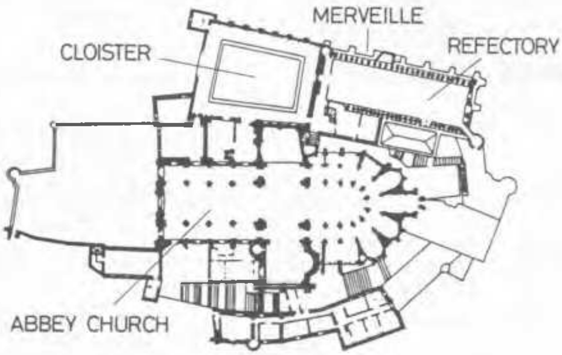


Fig. 56 - Mont St. Michel - Level of the church.

adapting elegant architecture to the exigencies of building on a steep slope. The buttresses appear to sit directly onto the slope: the foundation details are not known but it is certainly a daring solution, bearing in mind that the greatest bearing pressures are beneath the outer face. Usually a buttress is without great interest: at the Mont St. Michel they are one of the marvels that attract so many visitors each year.

2 - The stability of man-made slopes: the Pyramids.

Bearing in mind that the slopes of a rock-fill dam are typically chosen as 1 (v): 2 (h) from considerations of long-term stability, we as geotechnical engineers cannot help but be interested by a manmade slope 150 m high inclined at 52° to the horizontal that has stood for nearly 5 000 years: the Great Pyramids of Cheops. This structure represents the culmination of a development that began with the Stepped Pyramid of Saqqarah and continued through the pyramids at Meidum and Dahshur. The pyramid at Meidum (Fig. 58) is of particular interest and deserves to be studied in some detail before we turn to the Great Pyramid of Cheops.

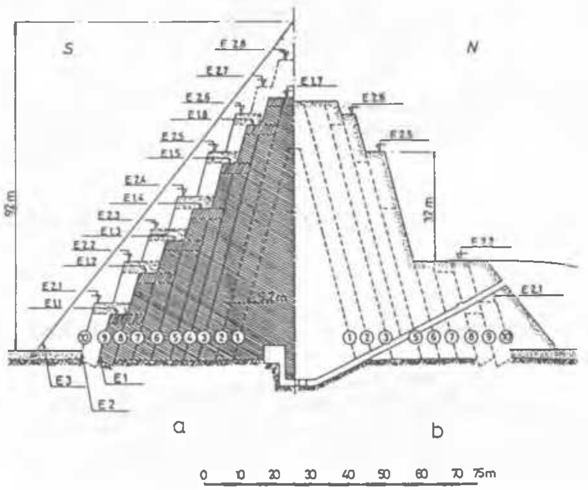


Fig. 57 - The pyramid of Meidum.
a) internal structure of pyramids $E_1E_2E_3$ after Maragioglio.
b) - actual profile.

The invention of Imhotep (III-3) of a honeycombed structure inclined at an angle, acting simultaneously as a retaining structure and as an internal buttress, was taken up by his successors, although with some variations. In particular the dimensions of the basic unit were increased from a width of 2.60 m to a width of 5.20 m. Now most of the walls are loaded equally from either side except for the outer walls i.e. the 'risers' of each step. It can be shown (see Annex III) that for a height of riser of 12 m, if the boxes were filled in a random manner, the 5.20 m section would not remain stable while the 2.60 m section would.

The pyramid of Meidum has an interesting construction history. It was apparently built in three stages (Fig. 57), the first two stages during the reign of Huni in the 3rd dynasty (2750 B.C.), and the final stage under the instructions of Snefrou, during the 4th dynasty. The first pyramid E_1 was a stepped pyramid of seven tiers which was later transformed into one of eight tiers E_2. It would appear that Snefrou later converted E_2 into a true pyramid E_3, being disatisfied with both the Bent Pyramid at Dahshur (instability) and the North Stone Pyramid (perhaps too small). The final height of the pyramid at Meidum would have been 92 m.

Recent excavations, in 1984, by the Service des Antiquités of the Egyptian Government have indeed uncovered part of the pyramid E_3 around the base of the ruined pyramid as it stands today. The faces are inclined at 52° to the horizontal which is the same angle as used for the Bent Pyramid and for most of the true pyramids.

Meidum is one of the most completely explored pyramids: Petrie (1910), Wainwright (1910), Borchardt (1928), Maragioglio and Rinaldi (1964). In particulr Wainwright undertook the excavation of a tunnel in a North-South direction that revealed the presence of a total of ten inclined walls. All the same many controversies still surround Meidum.

The curious shape of the pyramid has arisen from the removal of the upper part of the additional stone added to form the Pyramid E_3, together with the steps E_{2-3} E_{2-4} (of the second pyramid) and E_{1-3}, (of the first pyramid) (Fig. 57). This has left the sixth wall (counting outwards from the centre) exposed over a height of 32 m.

As discussed above we would expect this wall to become unstable at a height of 12 m whereas it is still standing at a height nearly three times this. The reason is that, as at Saqqarah, the stones were not placed in a totally random fashion: firstly they were shaped roughly and, because they were placed by hand, they tend to lie on planes that are approximately perpendicular to the face of the wall, that is at an angle of 18° to the horizontal on average. This would have the effect of greatly reducing the active force. In a small opening in the face of the exposed wall it is possible to see the filling material (Fig. 59). It is evident that the blocks are larger than those used at Saqqarah and that although they are only roughly shaped they are laid approximately in courses with the planes of contact being nearly vertical and horizontal. The material is certainly very superior to random rubble.

It is widely held that the material added by Snefrou to transform the pyramid from the shape E_2 to E_3 was later removed for use elsewhere (the word used by Maragioglio for this removal is smantellamento: he believes that the blocks were reshaped in situ, which explains the piles of waste

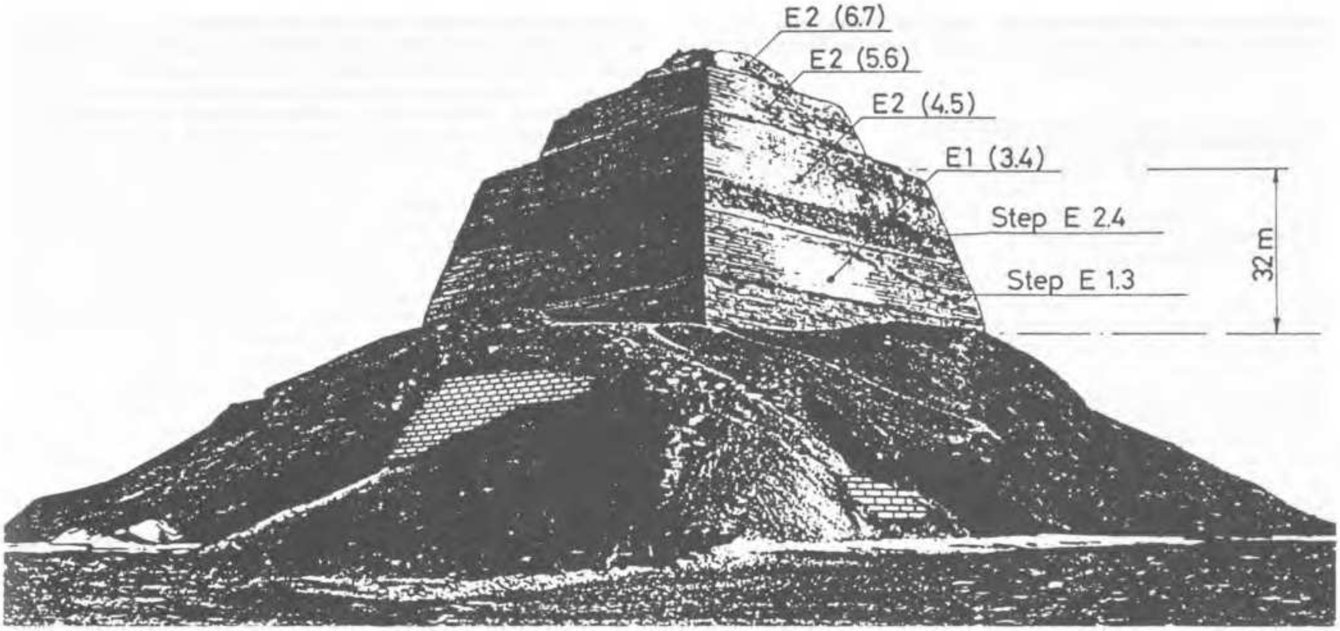


Fig. 58 - Meidum with excavation in progress during 1984. For notation see Fig. 57.

Fig. 59 - View of the filling material behind wall 6.

around the foot of the pyramid). The possibility of a slip failure does not appear to have been properly considered by the archaeologists.

The pyramids were always faced by blocks of Tura limestone and it is true that this material has been removed from all the important pyramids by later generations, for use elsewhere. Nevertheless all the other true pyramids, Dahshur, Cheops, Chefren, Mycerinos, have retained their original shape. We know that the stone filling at Meidum, coming from a local quarry, was of very poor quality, as shown by the laboratory measurements of seismic velocity carried out by the Laboratoire Central des Ponts et Chaussées (1984), where a value of 2 800 m/sec was measured, which compares with a typical value for sound limestone of 6 000 m/sec. It is difficult to see why, therefore, anyone should want to go to the lengths of removing this material from such a great height and reshape it for use elsewhere. In addition we know that this material would have exfoliated with time under the action of the sun and wind, which is sufficient explanation for why no complete blocks have been found in the rubble that lies around the base.

On the other hand the hypothesis of a slip failure seems very plausible: to begin with it explains the piles of rubble all around. Nevertheless the slip must have occurred in either the medium or long term because otherwise it is unlikely that Cheops would have attempted to build a pyramid twice as high as that at Meidum. Besides, the town of Djed-Snefrou that was located around the base of the pyramid (Yoyotte 1913) prospered during the reign of Snefrou, and it is unlikely that they would have wished to remain living next door to a crumbling pyramid - Posener (1976). Mendelssohn (1974), the cryogenics physicist, was the first to put forward the idea of a slip failure, although he believed that there was a parallel between the collapse of this pyramid and the short-term failure of the slag heap at Aberfan. Not only is the historical evidence against a short-term failure, but the cause of failure at Aberfan was water, whereas in Egypt it rains only about 12 mm per year. Nevertheless Mendelssohn's book had the benefit of drawing the attention of geotechnical engineers to this problem - Seed (1983), James (1984).

A failure in the medium term, related to the friability of the stone and to earthquakes, appears to me to be the most likely answer, for the reasons given below.

The contact stresses between large roughly shaped blocks that have not been accurately trimmed, and of which some carry no load at all, may be as high as several hundred times the average stress on a section - Barton (1978). The material being friable this would lead to the stones being progressively broken down, with a consequent redistribution of the loads, resulting after several centuries in a granular material at its residual angle of friction. The situation would be exacerbated by earthquakes.

Although there has been little seismic activity in recent years, we know that earthquakes took place in 184, 95 and 27 B.C., also on July 21st 365 A.D. when the consequent tidal wave drowned 5 000 inhabitants of Alexandria - Ambraseys (1984). Another earthquake overturned the lighthouse at Alexandria in 796 A.D. Some of the energy of the earthquake would remain in the pyramid structure as 'locked-in' stresses, thereby increasing the contact stresses between the blocks. Furthermore in transforming the pyramid E_2 into a true pyramid it was impossible to place the blocks in an optimum manner, while the outer faces of the E_2 structure would have acted as surfaces of weakness for potential wedge failures. Thus once the Tura limestone facing stones had been removed a wedge of granular material ABC would remain, standing at an angle of 52° and with an angle of internal friction close to the residual value. There would have been very little frictional resistance along BC and the wedge would have been pushed from behind by an active force above the step E_{2-5} (Fig. 60). It would not be possible to determine which individual blocks carried load nor the degree and extent of crushing of the blocks - R. Marsal (   ) but we know that an assembly of blocks of uniform size is more compressible than one where the size distribution is 'well graded', also that the weaker the stone the more compressible it is. Further it is known that, as in rock mechanics, the stresses are greatest at the toe of the wedge - Muller (1963). This led to the steps E_{1-3}, E_{2-3} and E_{2-4} being sheared off in sequence (on some of the faces evidence of this shearing movement can be seen).

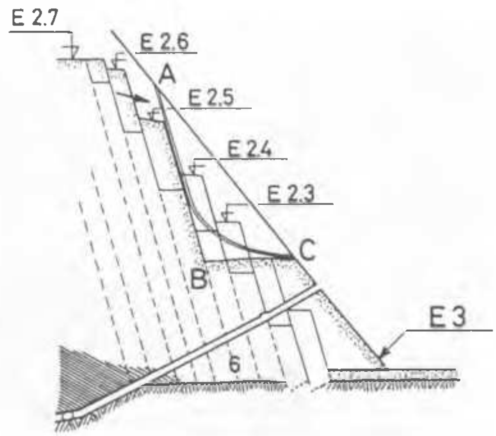


Fig. 60 - Instability of the wedge ABC. ═══ likely surface of long-term slip failure.

It is unlikely that the material from all four sides slipped simultaneously during a single earthquake. It is much more likely that this was a progressive failure involving successively larger volumes of material; the wind and the sun acting on this friable material would have accelerated the decomposition.

It would appear, therefore, that the collapse took place after the facing stone had been removed and certain evidence makes it possible to bracket the likely date of the failure. In an inscription found in the descending corridor made by two scribes of the 19th dynasty, 1 600 years after construction of Meidum, there is no mention of any important accident having taken place. However the slips must have occurred before the birth of Christ; in writing of his disapproval of the ostentation and greed of the Pharaohs Pliny the Elder makes reference to certain unfinished pyramids, of which one is listed as being close to Fayum. The largest pyramid close to Fayum is that of Meidum. Finally Greek graffiti found on the exposed face of the wall E_{2-7} means that this wall was visible during the Hellenic occupation of Egypt, which suggests a date of around 500 B.C.

We may conclude that the pyramid E_2 became exposed between 2 000 and 3 000 years after completion of the pyramid E_3.

As for the pyramid of Cheops very much less is known about the internal structure of this monument. We cannot even say if the 'silo' type of construction was used. We know, at least, that the blocks that are exposed have been shaped with much greater care than those at Meidum, which raises the question of whether the whole structure is formed of these large blocks. If this is so the power exercised (1) by Cheops to bring this about is truly astonishing for this would have involved cutting, with saws of non-tempered copper, in all 2 000 000 blocks of stone. After the excesses of Cheops and Chefren the size of the pyramids began to reduce with Mycerinos and at the same time the strength of the feudal system diminished.

A problem of geotechnical engineering related to the Pyramids : the access ramps.

The arguments over the techniques used for the construction of the pyramids continue to rage. There are those who believe that the blocks were raised from step to step using some form of lever apparatus (counterbalanced lift (Choisy), or a device based on the Shadoof (Croon) etc...).

The more commonly held view (Borchardt, Lauer, Edwards etc ...) is that some form of ramp built of sun-baked brick was used, in either a zig-zag shape or in a straight line perpendicular to one of the faces of the pyramid, of trapezoidal cross section. This latter view is supported by evidence of the remains of ramps of such a form at Meidum. Whatever the exact shape of the ramps, they pose two problems related to geotechnical engineering: the stability of the side slopes (the problem is similar in a way to the strength of the ziggurats and the requirement for horizontal reinforcement), and the gradient of the ramp itself. We know that the Egyptians used sledges drawn by human labour that slid on wetted silt: an example of this is shown in a relief sculpture on the side of the tomb of Djehutihotep, who was a noble of the 12th century (Fig. 61). The picture shows a large statue, that must weigh about 60 tons, seated on a sledge being drawn by a team of 172 men.

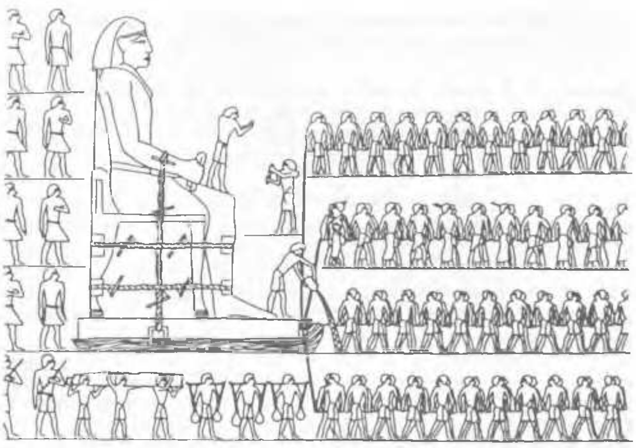


Fig. 61 - Transport of a large statue.

Three men are shown carrying pitchers, while one man pours water on the soil in front of the sledge to reduce the coefficient of friction. Three men behind carry a log with notches in it to wedge the sledge in position during a stop for rest. The silt probably came from the banks of the Nile. What would the coefficient of friction of the silt in its wetted condition have been? Knowledge of this parameter would make it possible to check whether estimates of the angle of the ramp (usually around 20°) are reasonable or not. It goes without saying that the figure depends on the water content, the bearing stress beneath the sledge and whether or not some form of skirting was

(1) If we are to believe Horodotus (II, 126) Cheops was not only excessively ostentatious but also extremely dissolute. Although not related to the stability of slopes, let me quote: "The depravation of Cheops reached such a point that having squandered all his treasures and wishing for others he sent his daughter into a brothel with instructions to bring back a certain sum of money, the amount of which is not known. Nevertheless she raised the money and at the same time, resolved on leaving a memorial in her memory, demanded a stone block from each of the men, with which she built the middle pyramid of the three situated in front of the large one. The sides of the base of her pyramid measure 150 feet each."

All I need to say is that this pyramid contains 20 000 stones!

provided to the runners to prevent the wet silt squeezing out sideways.

It appears that there have been no precise experiments to measure this parameter. Chevrier (1970) reports that a team of six men were able to pull a block of stone of $2m^3$ volume (about 50 kN) horizontally on wet silt. Since we do not know with what force the men were pulling the test does not give us a value of the coefficient of friction: assuming a figure of 0.1 means a pulling force per man of 800 N, or 0.05 means 400 N per man. If we take the figure of 0.1 and consider the same $2m^3$ block on a slope inclined at 20° the required traction force increases from 5 kN to 22 kN, which would require a team of 27 men. Based on a figure for the energy output of each man (800 to 1 000 Nm/sec) and knowing an approximate value for the coefficient of friction it would be possible to make a rough estimate of the time required to build a certain pyramid, and hence to decide whether it is likely that this was indeed the method of construction.

IV - DEEP FOUNDATIONS .

1 - Piled foundations

It is widely held that during the Neolithic age a form of construction of wooden houses built over water and supported on stilts, similar to those found in many parts of the world today, was in common use.

Recent archaeological excavations in Europe (Paret 1958) suggest that these buildings were, in fact, situated on the edges of the lake, rather than over the water. They first appeared around 5000 B.C. At this period in history the level of the water in the lakes was falling and it would have been relatively easy to force the wooden posts, on which the platform of the house was supported, into the soft sedimentary soils. With time the piles might have rotted or the soft soils settled which would explain why in some places several platforms have been found one on top of another. The case of the house founded on stilts actually over the water was in fact rather rare.

Such structures were common over a period of 3 000 years, through the Bronze Age, until the Iron Age. Whether over the water or on the edge of the lake the use of piles was common: the idea of piercing a hole in the soil by forcing downwards a sharply tipped pole was also used by the Incas (Fig. 62) with their digging stick, as well as by the Arab peasant (Fig. 63) after the discovery of iron.

However, with time, machines were developed for installing piles. The pile drivers used by the Greeks must have had many similarities with their war machine the "tortoise". (Fig. 64) This device was used for sieges and was a sort of tower on wheels with inside a steel-tipped battering-ram for breaking down gates and walls. Polydos of Thessalia, who was the engineer of Philip

Fig. 62 - Use of a digging stick by Incas (after Dumas).

Fig. 63 - Spade with foot support (after Dumas).

of Macedonia, used these machines to great effect in the siege of Byzantium. The battering ram can be seen as a natural progression from the first use of percussion by man, the shaping of flint arrowheads.

However this does not tell us what means were used for driving piles. In "Re Architectura" Vitruvius provides a summary of Greek and Roman practices: "In a site where there is no solid ground but only filled material or marshy soils it is

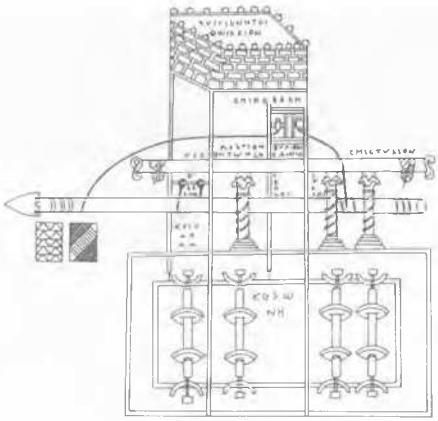


Fig 64 - Plan and elevation of the tortoise of Hegetor (from a Greek manuscript of the 10th century).

necessary to dig as deeply as possible, then to attempt to bail out all the water, and then to install wooden piles of alder, olive or oak that are slightly charred, hammered into the ground by machine, at very close spacing. The gaps between the piles should be filled with charcoal and the resultant foundations will provide a strong base to the structure".

We see that the wood for the piles could only be of a certain kind, but Vitruvius does not provide any details of the pile-driving machines used, which, as we have seen, he recommends also for compaction of loose soils. The use of charcoal between the piles is interesting, and it is possible that its purpose was to provide a drainage layer and to prevent the piles from rotting.

No doubt a good deal of research work would have gone into the development of the pile-driving machine, similarly for the problem of cutting off the pile heads below water level to ensure that they were permanently submerged and hence did not rot. Fig. 65 shows a device for sawing off pile heads, devised by Villard de Honnécourt (1250) who was one of the few architects of the Middle Ages to leave any note books. The device on the right of the sketch is apparently for the purpose of fixing the level of the action of the saw.

Leonardo da Vinci himself put forward a design for a machine for driving piles, as did Francesco di Giorgio (Fig. 66) whose device included quite a sophisticated winch and drop-weight arrangement.

However the hand-operated machines were not sufficiently robust for driving piles in firm soils, as we shall see in the next section. Another problem that has affected many old religious buildings, such as Saint Catherine's in Hamburg (Pieper - 1964), and numerous buildings in old Stockholm is rotting of the piles due either to a progressive lowering of the groundwater level or to fluctuations in this level.

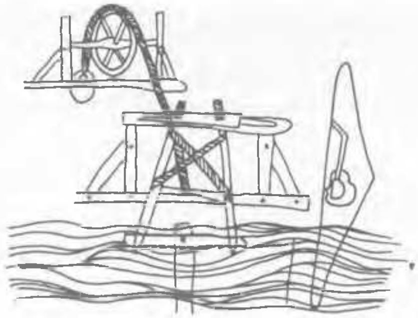


Fig. 65 - Saw for cutting off pile heads below water, devised by Villard de Honnécourt (around 1250).

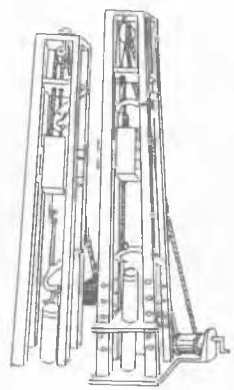


Fig. 66 - Drop-hammer piling rig designed by Francesco di Giorgio (around 1450),

Yet another problem that may occur in very soft soils is horizontal loading of piles due to surcharge. This has been a particular source of trouble for buildings on the island of old Stockholm. The piles were driven through a layer of very soft clay down to an inclined bed of hard gravel: lateral flow of the clay due to the weight of fill adjacent has led to heavy loads on the piles and the situation has been exacerbated by the general uplift of the Scandinavian continent such that some of the piles now lean at angles of as much as 20 to 30° to the vertical (Kérisel 1975).

2 - Caisson foundations

Besides piled foundations, caissons were frequently used for the support of structures in ancient times. For example the recommendations of the Sung Code are as follows: "if the soil is soft the hole shall be 10 chis deep (3.33 m) and it shall be filled with compacted material" (the compaction technique has been described in III - 2).

This type of foundation became popular particularly from the time that man first started digging to extract ores for metal production (iron, copper), and, where water was absent, rarely caused any difficulties.

V - FOUNDATIONS UNDER WATER .

1 - Breakwaters; caissons; the use of coffer-dams

Samos was famous in ancient times for three of the most impressive construction projects of antiquity, and it is not surprising, therefore, that Herodotus wrote at great length about the Samians. In addition to a fine temple and a tunnel that supplied the town with water, the Samians built a breakwater in water that is reputed to have been twenty orgyies deep (1) i.e. 37 m. This figure is hard to believe, however, and it would not be the first time the "father of History" had been inaccurate in quoting the dimensions of a structure. Nevertheless the port of Samos was much admired and we know that the Greeks had, by that time, overcome a number of problems associated with the construction of foundations under water, as evidenced by the jetties of the port of Cnidus and the sea wall, 1 300 m long, that linked the island of Pharos with Alexandria: Philon of Byzantium, from the 3rd century A.D., who was a member of the School of Alexandria, wrote a series of treatises one of which was entitled 'On the Construction of Ports', which has unfortunately not survived. Once again we find that it is Vitruvius who has written the definitive work on this subject.

In Chap. XII of Book V he provides a set of rules for the construction of foundations under water. The title of the book is "De portubus et structuris in aqua faciendis", or "On ports and structures under water".

To construct a breakwater Vitruvius discusses three possible methods :

- progressive filling out from the shore,

- inside a wooden caisson, below water, pouring a kind of concrete of stone blocks, pozzolana and quick-lime,

- building a double-walled coffer-dam. The gap between the two walls was filled with clay placed in sacks made from marsh reeds. The water inside the coffer-dam was bailed out by means of machines based on the screw principle, using a system of wheels and drums. The machines are described in Chaps. IV, V and VI of Vitruvius' Book X. They included a wheel with brackets attached, turned by a man walking inside the wheel, which also turned an Archimedean screw. Vitruvius goes on to say that "if the base of the dewatered excavation is not strong enough, it will be necessary to drive wooden piles which will form the foundations of the breakwater, and to include layers of free-draining material."

The first two methods were certainly commonly used in ancient times, the third less so, although the technique must be almost as old as the technique of piling since it involves simply a wall of clay in formwork held up by piles, and is not so dissimilar to the dams built by beavers. To work in the dry, however, it was necessary to have some efficient means of dewatering. The Archimedean screw in fact existed long before Archimedes himself, and was much used along the banks of the Nile: however these devices are clumsy and have a low output; it is true that the Greeks invented a form of suction-forcing pump, such as that developed by Ctesibios (Fig. 67), but the capacity of those machines and the heads of water involved meant that they were only suitable for use in very shallow locations and where the volume of water to be pumped was small. Nevertheless over the period which we are discussing great progress was made in this area, and as the 18th century approaches, in 1683, we find the first consul in Antibes marvelling at a temporary excavation that has been pumped dry, during the construction of the port: "It was an astonishing sight to see the base of the excavation dry thanks to a cofferdam that was holding back a head of water of more than 25 ft. The whole of the base had been levelled off by a gang of 2 000 workers. The material was hard, like a tuff. We even saw some of the workers playing football there. The cofferdam was carefully breached on 12th April 1683 and the next stage of the works was begun."

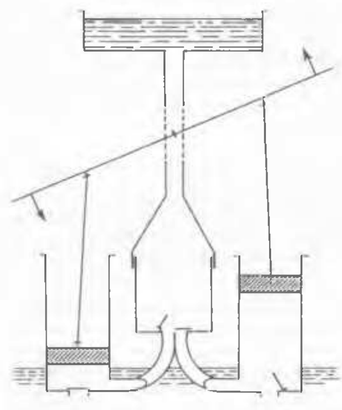


Fig. 67 - Suction-forcing pump of Ctesibios (after Choisy).

(1) 1 orgyie = 1.85 m

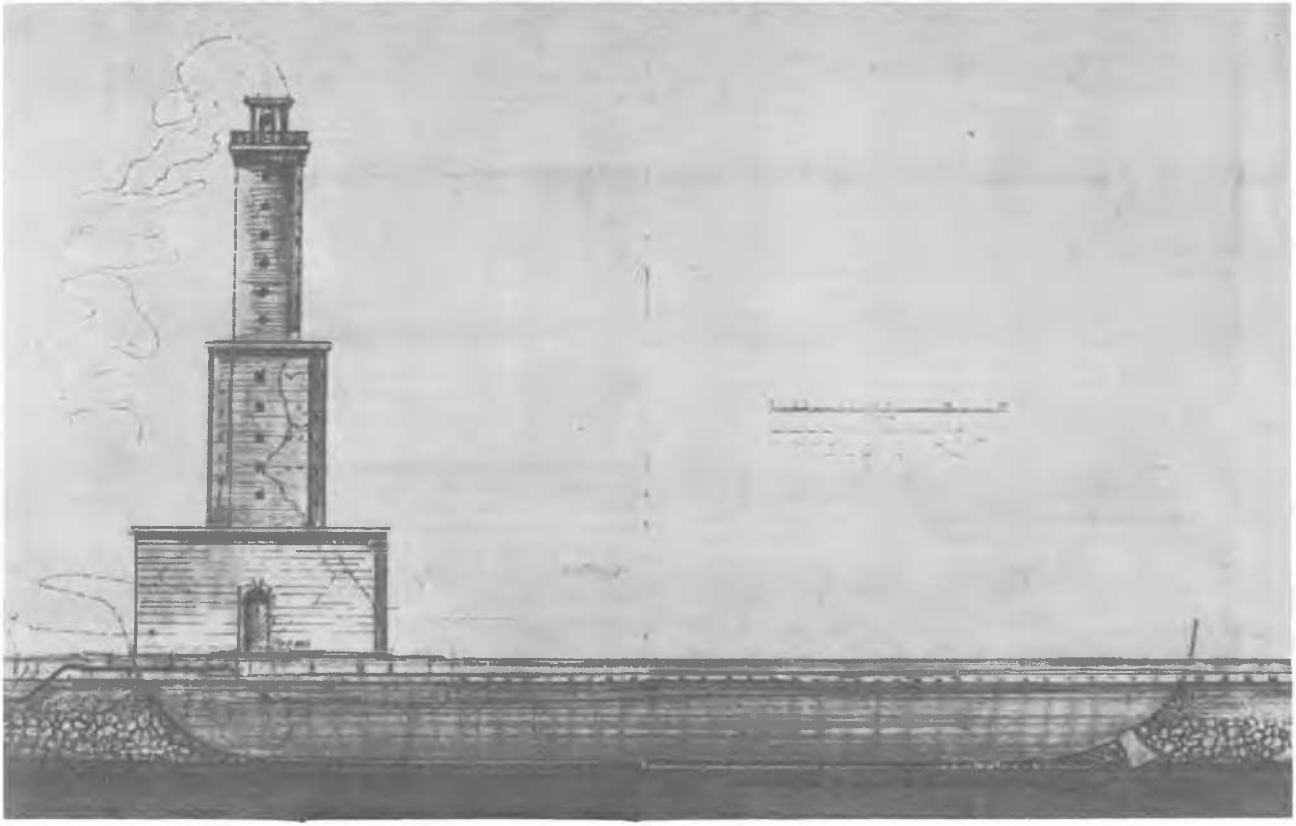


Fig. 68 - Probable form of the lighthouse at Ostia and its foundations.
Latium Archeologicum
Perm. Edit Il Turismo, Firenze

However other methods of construction were possible, besides the three proposed by Vitruvius.

2 - The lighthouse at Ostia: the first offshore platform

The Roman tradition of development of construction techniques continued after Vitruvius with the invention of the first offshore platform.

Despite Vitruvius' advice not to attempt to build a port at the mouth of the river, due to problems of silting-up, the construction of the port of Ostia, at the mouth of the Tiber, was begun in 42 A.D., during the reign of Claudius.

Suetonius describes the layout of the port in Chap. XX of Book 3 of his biography of Claudius: "The emperor created the port of Ostia in building two jetties, one on either side, in the form of an arc of circle, and a breakwater to bar entry to the port, in water that is quite deep; the breakwater was begun at the farther end, by sinking the ship that brought the obelisk from Egypt (1); using this as a base a large number of pillars were erected, which supported a high tower which was lit up at night to guide the ships, in the same way as the lighthouse at Alexandria".

Based on the description of Pliny the Elder and on recent excavations we know that this flagship was 104 m long, 20.30 m wide, had six decks and displaced 800 tons. The decks were taken out and the ship was ballasted with concrete and scuttled in 6 m of water. The lighthouse was located over the bows of the ship (Fig. 68). This foundation therefore formed an island. It was then joined to the mainland by sinking four smaller ships in line which formed the foundations for a new quay.

This first port at Ostia became entirely silted up and is now located inland from the shore.

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(1) This is the obelisk brought to Rome by Caligula, which can now be seen in St. Peter's Square.

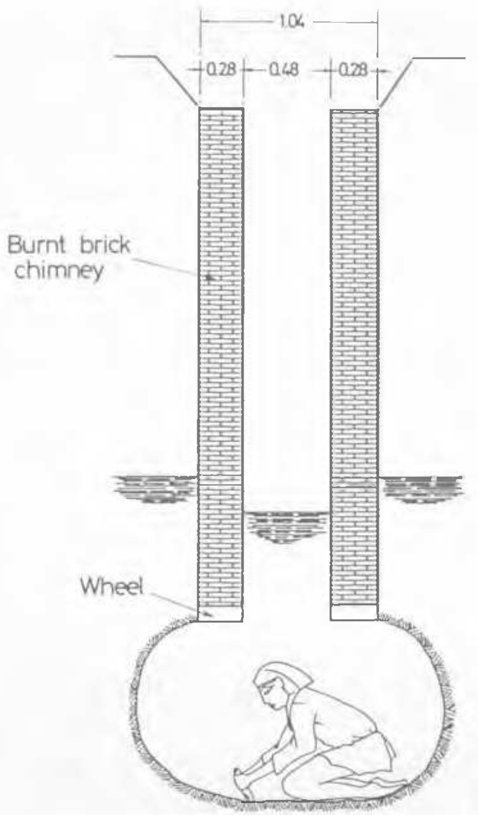


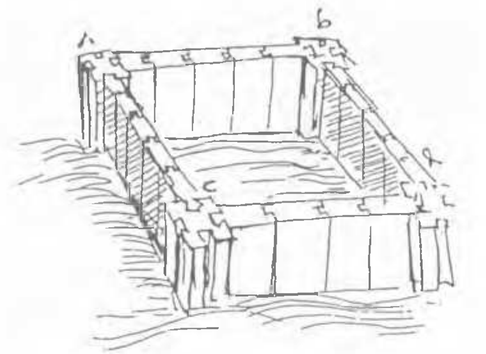
Fig. 69 - The zarbiyyeh, or Egyptian self-sinking caisson (interpretation of the description).

3 - The Egyptian zarbiyyeh: the self-sinking caisson

This form of caisson construction is described in the Kitab Al-Ifadah Wa'l-I'tibar of 'Abd Al-Latif Al-Baghdadi (1204). In the English translation by R. Hafuth Zand (1964) we read:

"As for the foundations, called in Egypt zarbiyyeh, these are very ingenious in their construction. This is how it is done. They make an excavation for the foundations until they reach dampness, and water begins to appear. Then they place a wheel made of sycamore wood or other similar, on the damp earth, after well levelling the place. The thickness of this wheel is in the neighbourhood of two-thirds of a cubit, (1) and the diameter of its circle, two cubits. Then they build on the wheel masonry in brick and lime to a height of twice a man's height, made like a kiln. Then divers descend into the wells; they continue to excavate and to measure the water out, and withdraw the earth and sand. They extend their digging all round under the wheel, and as soon as, by means of this digging, the wheel cannot carry, in the space that has been made, the weight of the masonry which it supports, it sinks. To measure the sinking, the divers continue their work, and dig under the wheel, while the masons, on their part, continue to build the building. Thus the masons do not cease building and the divers excavating, the masonry sinking always more and more by its own weight until it finds solid earth and can arrive at a degree of excavation which is known by the workers. When the first well is finished, they commence another similar, on the same lines, four cubits distant from the first. They continue to do this along all the length of the foundations; and when this work is done they lay the usual foundations after having filled the wells, which become like very solid piles which carry the building and the columns which uphold it."

(1) 1 cubit = 0.52 m



Modo di votare un porto: fa che questo sia 40 braci per faccia, e quando vi voto il fondo de detta cassa, lascia stare una de le face e stramuta l'altre 3 dopo quella, e rifarai altrettanto, e poi rivota e fa il simile.

"Means of emptying a port: make it 40 spans wide along each face: having emptied the caisson so formed, leaving one face in place form a second caisson adjacent, using the three other faces and then empty this in the same manner."

Fig. 70 - Leonardo da Vinci - Caisson for foundations below the water table.

Thus we find that the method of construction of foundations under water using a caisson sinking under its own weight existed as early as 1204.

The dimensions quoted are interesting for the interior diameter of the caisson would have been only 0.48 m (Fig. 69), so either the divers were very young or particularly thin.

A few centuries later Leonardo da Vinci proposed a rather large hydraulic caisson (Fig. 70).

Leonardo's notes are not very illuminating. The method described calls to mind Vitruvius' "Re Architectura" (Book V, Chap. XII).

Fig. 71 - Reproduction of a drawing with two representations of la Tour d'Ordre at Boulogne (France).

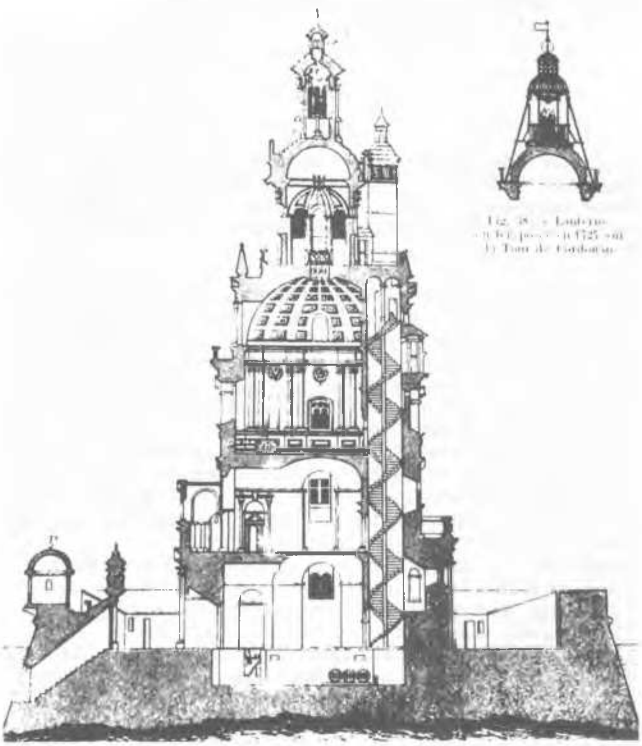


Fig. 72 - Section through the Tower of Cordouan, built by Louis de Foix - after Bélidor.

4 - Marine projects

With the exception of the lightouse at Ostia the ancients did not master the technique of construction offshore.

It should be noted that all the famous lighthouses of antiquity were founded on solid ground (E. Allard, 1889), including the lighthouse built at the Hellespont, on the headland of Sigea, in the days of Troy, also those at Khrusopolis and Abydos built on islands, the famous lighthouse built on the island of Pharos, next to Alexandria, around 300 B. C., the Roman tower on the island of Capri and the Roman tower of Hercules at La Coruna in Spain, etc ... Neverthless even built on solid ground the lighthouses of antiquity and the Middle Ages had their fair share of foundation problems. This was certainly the case for the Roman lighthouse at Boulogne, which it is believed was built by Caligula and later restored by Charlemagne; when built, the tower was located at a safe distance from the edge of the cliff. However, the rock in this area is of excellent quality and the local inhabitants opened up underground quarries which they extended rather too far. This action and particularly the erosion due to the waves and the effect of the seepage of ground water, led to undermining of the cliff: the tower, shown in Fig. 71, collapsed in three stages between 1640 and 1644.

The drawing on the right was copied from a painting made at Boulogne when the tower was still standing. The sketch on the left was taken from a carving on a chair in Boulogne, made in 1549, i.e. when the town was still occupied by the English.

The first lighthouse constructed with the foundations under water was the celebrated Tower of Cordouan, built by Louis de Foix between 1584 and 1610. The site is at the mouth of the Gironde, in France, on a rock under 3 m of water, where the currents are strong. Fig. 72 is a section through the tower taken from an engraving in "l'Architecture Hydraulique" by Bélidor (1753). The tower was circular and the diameter at the base was some 40 m. Fifty years after completion of construction it was necessary to carry out some quite substantial repairs at which time it was noted that part of the structure was not founded directly on rock but on a wooden framework.

The most famous lighthouse site is the Eddystone Rocks, some nine miles off the south coast of Cornwall. The first lighthouse on this site was built of wood by Winstanley in 1696 and was only 60 feet high. It was soon found that the waves sometimes reached the light itself and so the lighthouse was enlarged. The height of the enlarged structure was about 120 feet.

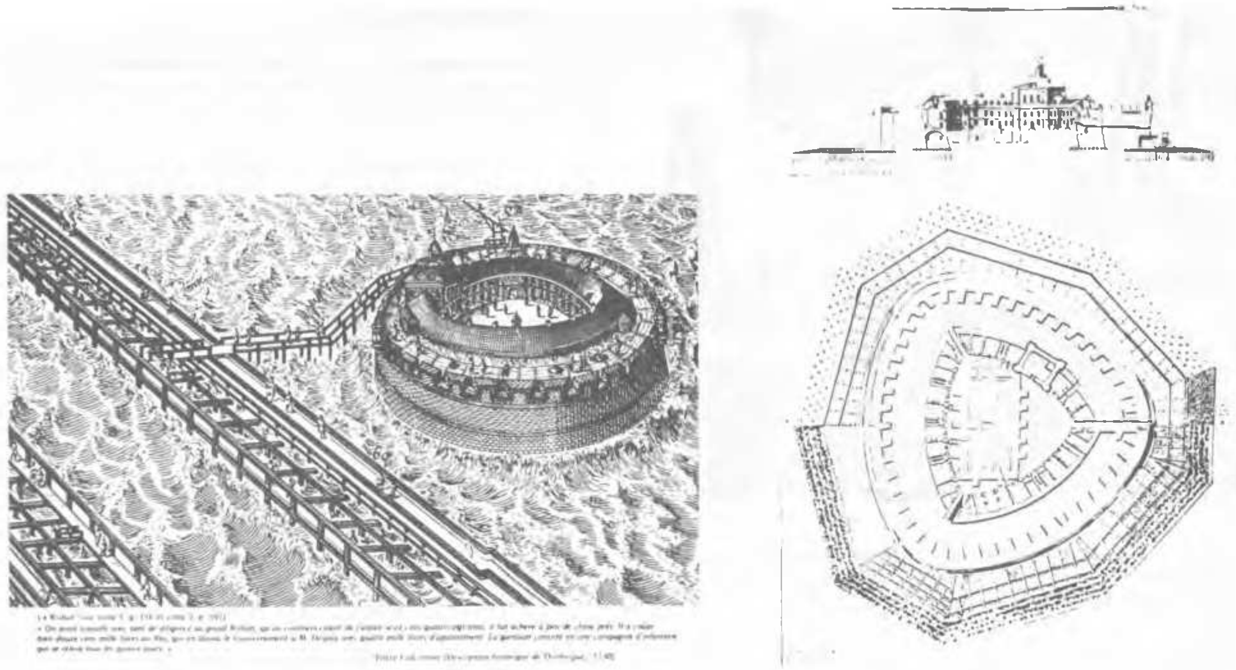


Fig. 73 - Left : the Risban at high tide.
Right: . above - cross section through diameter.
. below - horizontal sections above protection works (upper), through protection works (lower).

One night in November 1703 Winstanley and his builder were in the lighthouse as some repair works were being carried out, when an exceptional storm blew up and the lighthouse was destroyed taking its occupants with it.

Louis de Foix made the mistake of using a wooden framework between the base of the structure and the rock. Winstanley's structure collapsed because of structural weaknesses, insufficient weight, and a poor connection with the rock (D. A. Stevenson (1959)). In both cases the mortar was probably washed out by the waves in places. It was not until 1756 when Smeaton built the fourth Eddystone lighthouse that a mortar suitable for construction in the sea was found.

5 - Measures taken to overcome the problem of scour

Scour has led to problems with foundations since the earliest times. The recommendations of the Sung Code for protection against scour were that the element in question should have a length of at least 6 m in the direction of the current, and that a screen of 5.6 m long piles should be driven at a distance of 1.6 m.

For the protection of jetties in an outer harbour Bélidor recommended a width at the base equal to three times the height, with berms on either side, the width of which he did not specify.

The Risban (1) at Dunkirk (Fig. 73) was built by Vauban towards the end of the 17th century and was described by Bélidor (1737) as the most impressive of all fortifications built in the sea. The structure was founded "on a bank of moving sand" (2), was 15 m high and was located a distance of 1 000 m from the shore. The fort was elliptical in shape and the outer walls were founded at a depth of only 0.6 m and were built without recourse to a coffer-dam. Protection against scour was provided by means of a berm some 20 m wide that surrounded the fort. A layer of fascines was placed over the outer 9 m of this berm, and was covered in turn by a layer of stones. Between this ring and the fort itself a series of wooden sheet-pile walls were driven, to a depth of 1.8 m. Between these the sand was dug out to a

(1) A fortified platform defending the entrance to a harbour.
(2) Letter from Vauban to Vuorden .

depth of 0.6 m and replaced by compacted clay through which small wooden piles were driven. Above this a honeycombed wooden structure filled with cobbles was built (1). We see, therefore, that Vauban preferred to combat erosion using a system of protection that was wide rather than deep (2). On completion of the berm the foundations for the walls were built by digging in bays, under Vauban's instructions, limited to a plan area of some 2 m x 2 m, or to twice this.

6 - Bridge foundations

Foundations for bridges up until 1700 showed the same insufficiencies as other foundations built under water, although at the same time were often highly ingenious.

The piers of bridges were often founded on rock fill or on mounds formed by throwing baskets filled with small stones into the river, or into a wooden caisson sunk onto the river bed, until the required level was reached. Many of these bridges have long since collapsed due to scour around the piers.

In general, however, there is very little information on the foundations of bridges from ancient times. The bridge over the Euphrates at Babylon was 110 m long; the piers were spaced at intervals of 9 m and were 9 m high and 21 m wide. Forbes (1955) states that they were built of brick with a bituminous mortar, and that the base was provided with a protective coating of bitumen. We do not know how the foundations were built, however. Similarly it is known that the piers of the Sant'Angelo bridge in Rome are founded at a depth of 5 m below the bed of the Tiber, but one can only guess at the construction techniques employed.

Based on archaeological excavations at the sites of bridges built over the Garonne, in Toulouse, during the Renaissance, and on a study of archival material, R. Lotte (1982) has been able to establish the methods used for the construction of the foundations of the piers. They were apparently built inside coffer-dams formed from driving two concentric circular sheet-pile walls and filling the gap with puddle clay. The individual piles were wooden planks fitted with an iron shoe (Fig. 74) and placed one against the other so as to form a continuous wall. They were driven by a hand operated weight and therefore did not penetrate very far into the marl that lay beneath the alluvium. This would have meant that deformations were likely, and that there was a danger of the coffer-dam being swept away by the current.

This problem was overcome towards the end of the 16th century by the invention of the anchored pile i.e. by driving the piles into a pre-bored hole in the hard strata: the head of a device used for pre-boring was found by R. Lotte in 1938 (Fig. 74), which consists of two cutting edges turned on a helix. Connected to this head is the broken-off stump of the main shaft which would have been connected to a horizontal bar that acted as a lever for turning the head. By means of pre-boring and by fitting the sheet piles with iron shoes it would have been possible to reach sufficient depth to mobilise the passive pressure required to prevent the coffer-dam from sliding.

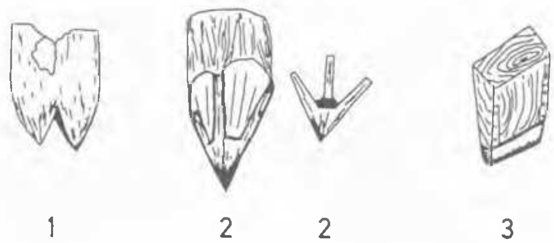


Fig. 74 - Implements excavated from the foundations of a bridge built during the Renaissance at Toulouse, France (R. Lotte - 1982)).

1 - Head of a pre-boring auger
2 - Pile shoes
3 - Shoe for a sheet pile

In a similar way piles were installed inside the coffer-dam and built into the masonry in order to ensure the stability of the pier itself.

The Italian engineers must also have been aware of the problem of lateral forces on piers because Fontana, a doctor in the Venetian Republic, invented a machine for breaking up hard material under water (Fig. 75).

These two inventions, Fontana's machine and the techniques of preboring, were not the only advances made during the 16th century

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(1) Bélidor, Arch. Hydraul. Based on a quotation obtained by Vauban from the contractor.

(2) Built between 1680 and 1683 the Risban was demolished in 1713 in accordance with the Treaty of Utrecht, but later rebuilt. In 1808 it once again dominated the entrance to the harbour, but it became damaged by storms and by 1830 had been completely destroyed.

in the field of bridge foundations. Before construction of the bridges at Toulouse began, the master builders to whom the contract had been awarded undertook a form of ground investigation by probing with a 7 m-long iron bar, given the name 'espreuve', to determine the thickness of the alluvium above the marl.

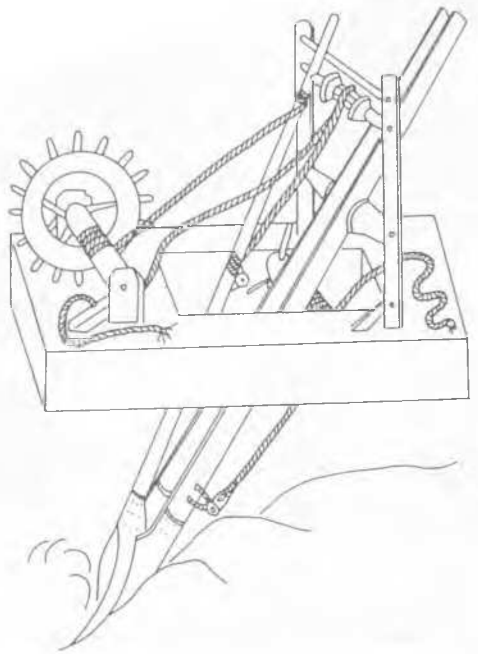


Fig. 75 - Machine for breaking up hard material underwater, invented by Fontana (1540-1614).

There is little doubt that this technique was adopted for use elsewhere during the 17th century for in 1716 in Gauthey's treatise on bridges we read:

> "Tasks to be performed prior to construction of a bridge ...
> No. 5) Using iron rods, probe the ground and take samples"

In the 16th century Leonardo da Vinci himself designed an auger device for boring in soil (Fig. 76), although, like much of his work, a prototype may not have been built at that time.

Here is the translation of Leonardo's notes that accompany his sketch:

> "If you want to make a hole in the ground easily, you can do this with the device illustrated; the screw may be advanced into the ground by means of turning the lever m-n in a right hand manner. Having reached the desired depth, with m-n fixed, turn the lever f-g in the opposite sense: this will make the screw rise without turning, bringing the soil with it".

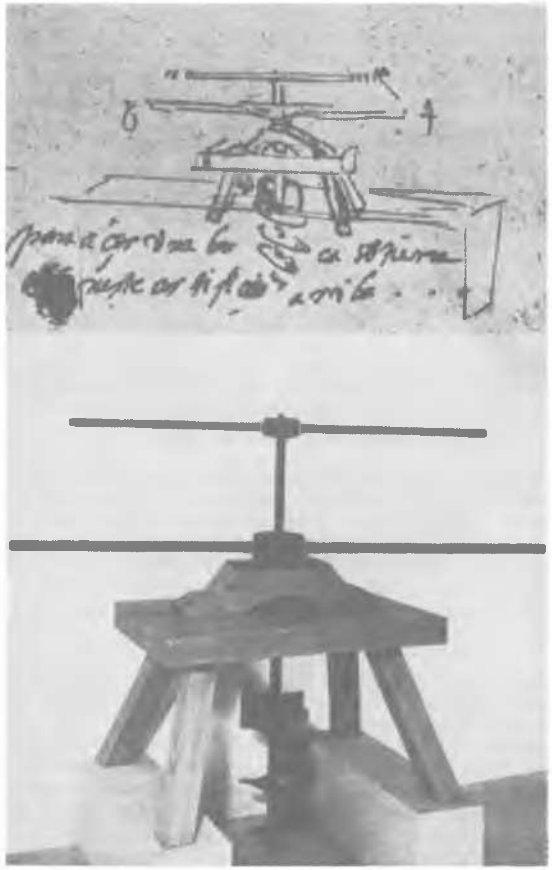


Fig. 76 - Leonardo da Vinci's design for an auger-boring device for soil, with below a model built in Italy based on the sketch.(1)

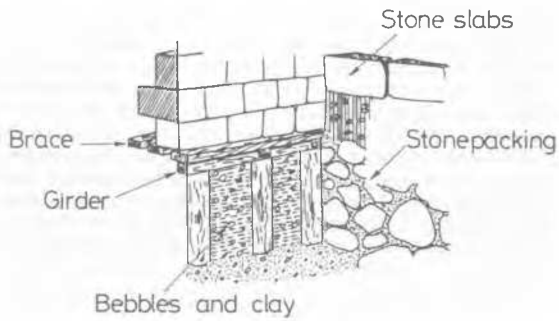


Fig. 77 - Foundations of a pier on sand: the bridge of Beaugency, earlier than 14th century (Waschkowski et al. 1981).

Despite the advances made in site investigation techniques and the installation of anchored piles it was still

(1) The Chinese developed a spoon-auger, known as a Loyang spoon, at a very early date (Lu Zhao-Jun (1974)).

very difficult to build foundations on a sandy river-bed, and they remained highly susceptible to scour. Fig. 77 shows the foundations of one of the piers of a bridge at Beaugency (earlier than the 14th century); the masonry of the pier rests on a wooden base supported on a number of short wooden piles driven into the sand (Waschkowski et al. 1981).

Venice provides two interesting examples of bridges founded on compressible silty/clayey soils.

Rialto Bridge

Rialto Bridge (1588-92) comprises a single span of 26.40 m and was designed by Antonio da Ponte. The bridge is founded on alluvium and special measures were taken to ensure its stability: beneath each abutment 600 piles 15 cm in diameter were driven at close spacing, each 3.30 m long, in three groups, and inclined joints were used in the masonry (Fig. 78). These measures were successful, although it is worth noting that because of group effects it would have been more efficient to use fewer, longer piles.

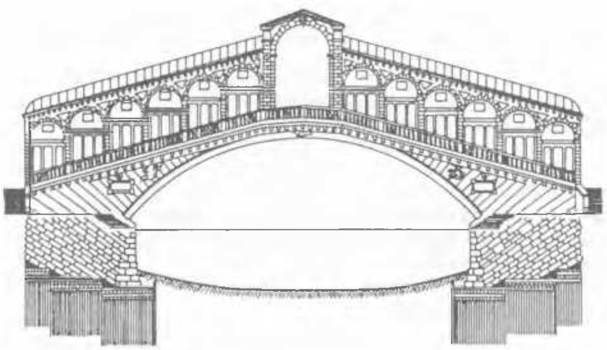


Fig. 78 - Rialto Bridge (Venice) - end of 16th century.

The "Tre Archi" bridge in Venice

One hundred years later rather less care was taken over the foundations for the "Tre Archi" bridge in Venice. Built in 1688, this bridge was restored in 1979-80 using the technique of root piles, which were installed by Fondedile. The piles were drilled through the masonry, so it was possible to establish the founding levels of the piers and abutments, and the soils conditions beneath (M. Giusti et al. 1980). It turns out that the abutments were founded at a very shallow depth, while the piers were built directly on the river bed. (Fig. 79).

Fig. 79 also shows the soil strata: the bridge is founded on a layer of clayey silt between 3 and 4 metres thick, which overlies

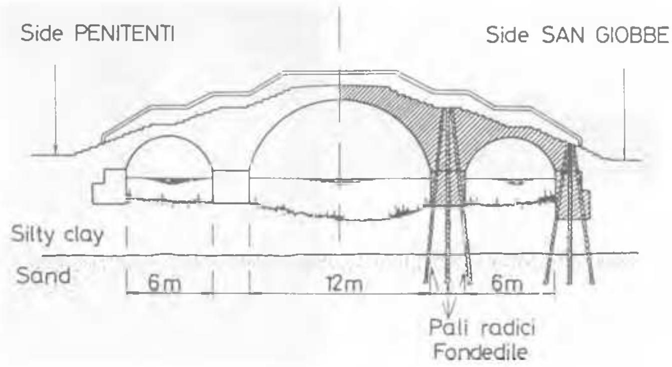


Fig. 79 - Longitudial section through the "Tre Archi" bridge, Venice, with a half section showing the root piles installed.

a layer of sand. The heavy parapet, added at a later date, and the compressible nature of the silt explain the large differential settlements measured in a survey made in 1979 (17 cm between one of the abutments and the adjacent pier). It would appear that the intermediate piers were built inside wooden caissons lowered onto the river-bed, and that small coffer-dams were erected for the construction of the abutments.

The remarkable bridge at Anchi in China

We have seen, therefore, that prior to the 18th century sandy soils as well as marls and clays posed difficulties for the construction of bridge foundations. This makes the bridge at Anchi, built between 605 and 617 A.D., seem all the more remarkable. It is the oldest surviving bridge in China, yet its elegant architecture has quite a modern appearance, as seen in Fig. 80.

In contrast to the "Tre Archi" bridge the architect Li Chun avoided the use of piers and spanned the river in a single, rather flat, arch, 37.4 m long between the faces of the abutments; the voids formed by the secondary arches both reduce the dead weight and allow the passage of water at times of flood. This bridge has survived 1 300 years of traffic, earthquakes and floods and is rightly considered as a masterpiece of its age.

The Geotechnical Engineering Office in Peking has undertaken a study of the foundations of this bridge. The abutment footings overlie a 7 m-thick layer of a sandy clayey soil, which overlies a layer of clayey sand. Laboratory tests on the upper material show a voids ratio of 0.63, a plasticity index of between 6 and 8, and a bulk density of 19.5 kN/m^3, so the soil

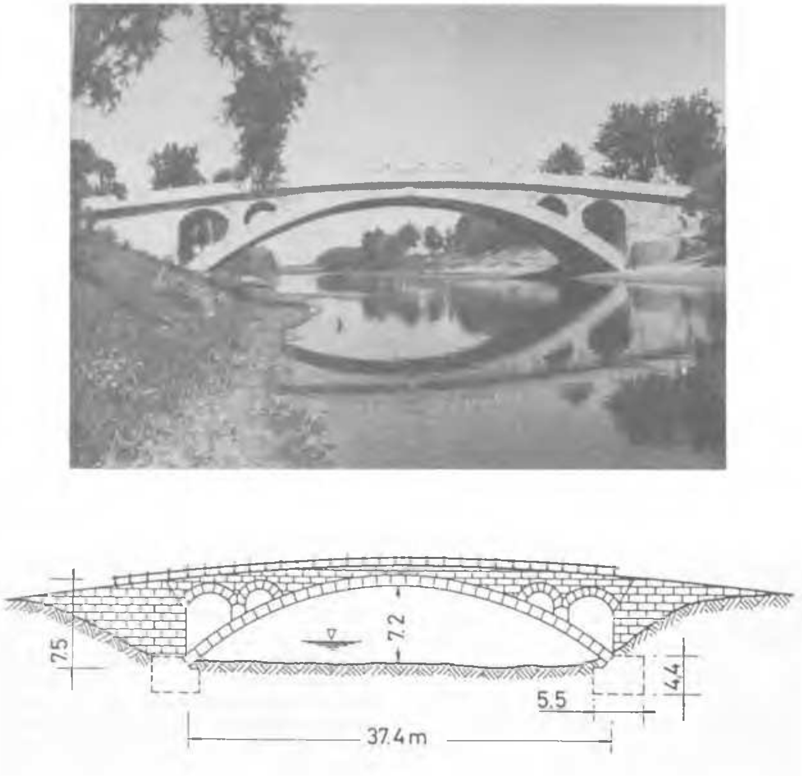


Fig. 80 - Above, the bridge at Anchi in China, Built around 600 A.D. Below, a longitudinal section, after Lu Zhao-Jun (1984).

is reasonably dense. The dimensions of the footings are 5.5 m parallel to the axis of the bridge and 10 m parallel to the river, which is the same as the width of the bridge. The total thrust at each abutment must lie between 17 and 24 MN, the vertical component of which could be supported by the soil without excessive settlement. On the other hand the horizontal component is relatively large: even if we take a coefficient of friction of 0.3 (PI 6 to 8) along the base of the footing the required passive force is still 24x0.8 - 24x0.6x0.3 = 14.9 MN. The area of the front of the footing is

$4.4 \times 10 = 44 m^2$ and the average depth about 7.5 m so the required coefficient of passive resistance is about 14 900/44x20x7.5, or Kp=3. This is somewhat high bearing in mind that in order to avoid damage to such a shallow arch movements must be small. Clearly friction on the sides of the abutment must play a role, and the degree of compaction required for the backfill must have been very high: one has to admire the skill and daring of the bridges' architect Li Chun.

VI - RETAINING STRUCTURES.

Retaining walls and buttresses are found in the very oldest structures and, whereas the builders would not have known how to calculate the earth pressures, they knew how to dimension the elements to carry these foundations.

1 - In Mesopatamia

The American Tobler and his colleagues from the University of the Museum of Philadelphia have undertaken archaeological excavations in Tepe Gawra, in northern Mesopotamia, that reach far back into history. At the greatest depths (layers XVII to XX at 27 m depth) they have uncovered certain circular structures (Fig. 81), some 5 m in diameter, that date from the 5th millennium B.C., which were supported by buttresses.

Similarly the temple at Tell Agrab, in the region of Sumer in southern Mesopotamia, is symmetrical in shape, and the inner court is supported around the outside by buttresses.

The ramparts of the great esplanade at Ur, supported by both external and internal buttresses, have already been described in section II 4 - 1. The ziggurat itself measured 62 m by 43 m in plan and was 20 m high and would have included both retaining walls and buttresses (Fig. 82).

Similarly we have already discussed (ibid.) the quay walls along the banks of the Tiber (1300 B.C.).

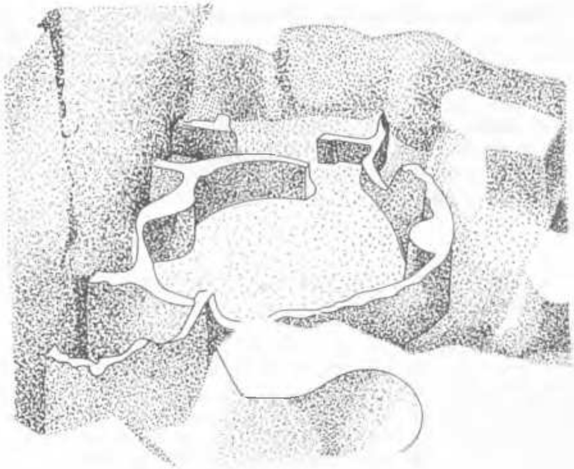


Fig. 81 - Circular structures at Tepe Gawra, supported by buttresses - 5th millennium B.C. (after Tobler (1950)).

However more impressive were the Hanging Gardens of Babylon, one of the Seven Wonders of the World and known to the Romans as "pensilis hortus", built by Nebuchadrezzar II around 600 B.C.

Based on the archaeological excavations of Koldewey (1914) the gardens would have appeared to "hang" because the supports hid a deep groove in the hill: these supports were of the form of barrel vaults with a vertical axis and a radius increasing with height, that is they were seven half-frustums in contact with the ground. The thrust from these was taken out by the spurs and by buttresses outside (Fig. 83).

2 - The Greeks

The Greek stoas, which were considered in section III-2, could be quite extensive and on sloping ground this required cutting

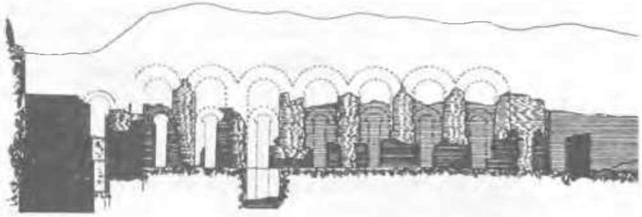


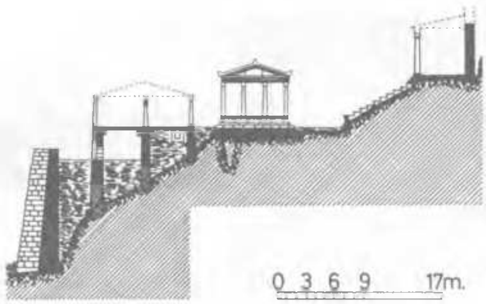
Fig. 83 - Horizontal section showing the, supports for the Hanging Gardens of Babylon (after Koldewey).

into the hillside behind the structure, and building a retaining wall in front and backfilling to form a platform. Sometimes the retaining walls were inadequate and became severely damaged by the earth pressures, as was the case with the stoa of Attalus at Delphi. However this was only rarely the case and generally the retaining walls built by the Greeks were heavily over-proportioned. For example at the Argive Heraeum one of the walls has a minimum thickness of 3 m and has, in addition, counterforts that are founded 2 m below ground level, with further counterforts (0.9 m thick) extending 0.50 m into the stoa.

It was only later, in Asia Minor, that the Greeks refined the design of retaining walls.

The finest example of a retaining structure from antiquity must be that at the temple of Demeter at Pergamum (2nd century B.C.) (Fig. 84). To build a terrace in front of the temple required a wall some 14 m high and 85 m long with counterforts in front and behind at equal spacing. The stone blocks used were relatively small and a mortar of lime with sand and clay was used for the joints. In addition an adit was dug beneath the wall to give access to the terrace, and beneath the adit a number of utilitarian rooms were built: this is a fine example of the elegant and functional architecture of the Attalids.

Fig. 82 - The ziggurat of the moon god Nanna, at Ur (around 2300 B.C.).



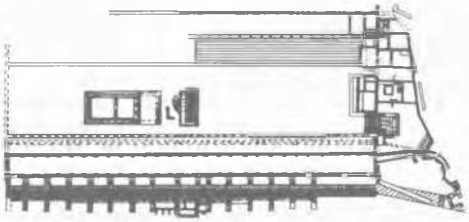


Fig. 84 - Vertical and horizontal sections of the retaining wall and the terrace of the temple of Demeter at Pergamum.

However the main reason for the development of the construction of retaining walls was a military one. Stronger defences were needed as the enemy war machines (catapults, battering rams etc ...) became more sophisticated. Thus the various rulers turned to engineers for advice. Since the tallest siege towers were nearly 60 m high it can be seen that even then large retaining walls were being built. The treatises on fortifications of the School of Alexandria (Philon of Byzantium) show that the Greeks were aware of the importance of the ratio between height and thickness of the wall.

3 - The earliest literature on earth pressures.

Once again the first text on earth pressures is found in Vitruvius' Re Architectura, Book I, Chap. VIII. Regarding the construction of ramparts for forts he recommends that one should "form ditches that are very deep and broad, at the bottom of which can be dug the foundation for the wall, which must be sufficiently thick to hold back the soil". He strongly recommends using internal counterforts:

> "A series of supplementary walls should be built ... to form the shape of the teeth of a saw or of a comb: by this means the earth is broken up into compartments and cannot push on the wall with such a great force". (1)

In Book VI, Chap. X, Vitruvius adds:

> "Great care must be taken to ensure that the walls are truly vertical, that they do not lean one way or the other: this is particularly true for those walls acting as foundations because of the damage that can be caused by the earth behind pushing on the wall". (1)

4 - Retaining elements incorporated in the American pyramids

There are certain similarities between the American pyramids and the ziggurats of Mesopotamia, both in their purpose and the form of construction. Both are climbed: the former for sacrifice, the second for prayer in a temple; both are built of earth (with the exception of some Mayan pyramids in stone with very strong mortar joints, such as Tikal and Uxmal). The American pyramids however, are characterised by a tiered form with intermediate retaining walls of stone which strengthen the structure. Nevertheless despite this strengthening the average side slope of the American pyramids is still much less than that of the Egyptian stone pyramids, as illustrated in Fig. 85: this shows the two tallest pyramids from each continent - in Egypt the Cheops pyramid (146 m high) and in Mexico the Pyramid of the Sun at Teotihuacan (60 m high). The bases of these two pyramids have approximately the same dimensions.

As shown the average side slope of the Temple of the Sun is 36°. A tunnel through the pyramid has revealed that behind the facing of stone and mortar there exists a capping 20 m thick of sun-baked bricks with stones, surrounding a core of clay which includes a few stones but no internal buttresses: the archaeologist Batrès has unwittingly demonstrated that if the facing is removed over a large area the material inside will flow out with the onset of the first rains.

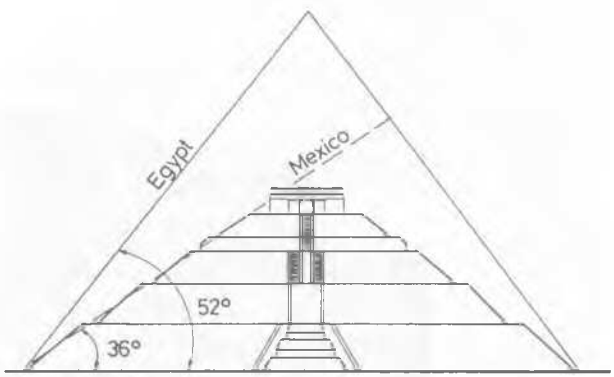


Fig. 85 - Cross sections through the Cheops pyramid and the Temple of the Sun at Teotihuacan.

(1) My underlining.

Many of the other Mexican pyramids have side slopes as great as that of the Temple of the Sun but the construction work is not so regular: at Teotihuacan the slope is broken up at intervals by the inclusion of a vertical tablero which can include sculptures in stone or ceramic. This is an ingenious device made possible by the use of large blocks of stone (Fig. 86).

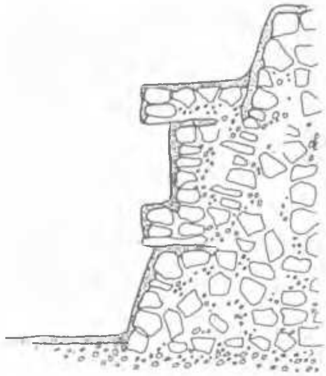


Fig. 86 - Teotihuacan: the Citadel. Reconstruction of a talud-tablero.

The pyramid of Tepenapa at Cholula, which was mentioned earlier because of its enormous size, looks like a sizeable natural hill. However it is of little interest to geotechnical engineers because of the modest side slopes (25°) and because it was built in several stages, the history of which is difficult to trace.

On the other hand the pyramid at Cuilcuilco (500 B.C.) is interesting because it was buried in lava from the nearby volcano Xitle, and so was effectively frozen at a moment in its history. This pyramid was built in several stages: firstly a retaining ring (1) (Fig. 87) which was later enlarged (2). The interior was then backfilled in two stages (3) and (4). The fill has creeped and pushed out the retaining structures, thereby increasing the overall diameter and presenting a concave shape to the sky (Fig. 87).

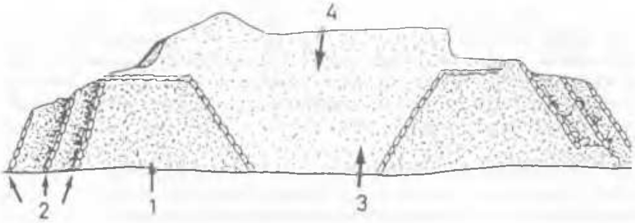


Fig. 87 - Cuilcuilco. Section across a diameter after removal of the lava.

The presence of a capping layer in the Temple of the Sun shows that the form of construction of the two pyramids is essentially the same. However, the Teotihuacan pyramid was built in one stage only, unlike the pyramid at Cuilcuilco.

5 - Retaining structures as the 18th century approaches

There were several treatises on fortifications written during the Middle Ages and the Renaissance (Francisco de Giorgio (15th century)). At a later date Louis XIV, who fought several wars, appointed Vauban as General Commissioner for Fortifications. Vauban went on to build some 300 forts. Although he made only minor improvements to the construction techniques already in use, he had some worthwhile ideas regarding ground conditions.

In 1684 he went to the length of publishing a standardising document entitled: "Table explaining the measures ... for building walls 10 to 80 feet high ... based on experience of the construction of four million cubic metres of stonework in 150 forts, built on the orders of the King." This is half way through his career, therefore. He recommends the use of internal counterforts, with a spacing of 5.40 m centre to centre. The wall itself was to be set back from the front of the foundation, thereby ensuring a better distribution of stresses. The paragraph that concerns the required thickness of a wall amounts to a recommendation of a thickness at the base equal to $0.20\ H + 1.48$ (metres). The length of the counterforts added was equal to about half the height of the wall. The depth of the foundations is not given and it is stated that the recommendations apply to "average soil conditions". Vauban found out that clayey soils could present special difficulties.

An entry in his diary dated 25th June 1699 is particularly interesting in this regard. It concerns the protection works for a lock at Bousinghe in Belgium (now called Boezinge, it is close to Ypres (or Ieper)). He notes that the old protection works had suffered distortion because:

> "The ground here is so bad that an embankment built at a slope of 2 to 1 will not stand up. It leads to continuous slips ... the material is fat and spongy with little strength and when it dries out it cracks and crazes all over with deep fissures that may be one, two three or four inches wide. When it rains the cracks fill with water and the soil becomes slippery like soap, which provokes landslips to a distance of 30 or 40 paces

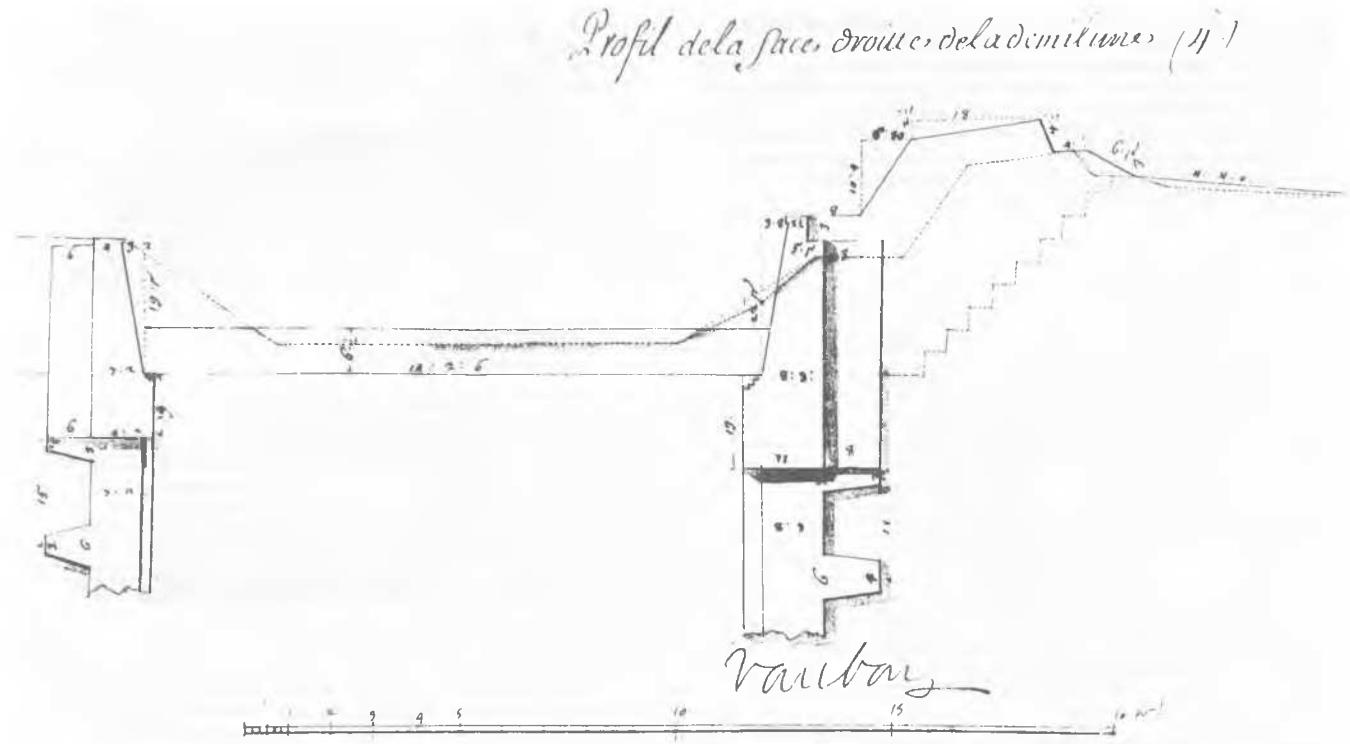


Fig. 88 - Two retaining walls founded in clay, designed by Vauban for the fortification of Ypres (1699). Archives Insp. Génie Vincennes.

(1) over a height of 20 to 25 feet. There is no other solution but to rebuild the wall while founding it on the boiling sand (2), if this is not at too great a depth: where the sand is too deep the thrust of the soil behind must be transferred to the soil in front by burying the toe of the wall at sufficient depth".

We see that Vauban appreciated the concept of passive resistance of soil. He also recognised that the soil conditions at Bousinghe were the same as those at Ypres, where a failure had occurred some twenty years earlier, in 1678. The foundations of the ramparts had slid forward while at the same time the wall had rotated backwards under the action of its own weight together with the friction force on the back face: further the counterforts had sheared off at the connection with the wall.

For the problems at Bousinghe and Ypres Vauban considered that artificial measures such as sheet piles, circular piles or passive berms would have been difficult to execute and probably ineffective. He also realised that counterforts were not suitable for clayey soils as they could not guarantee that the wall would remain monolithic. For these reasons, wherever the probes did not encounter sand, Vauban made use of the passive resistance in front of the wall by increasing the depth of the foundations (Fig. 88). A calculation in Annex IV shows what effect this has.

In some cases, for the failure at Ypres, where a wall had not moved too much Vauban reduced the load on the back of the wall and then, using temporary shoring, underpinned the wall in bays (Fig. 89).

In conclusion, through Vauban's writings and drawings we see the nucleus for the advances in understanding of retaining structures made by the engineers of the 18th and 19th century, as will be described by A. W. Skempton in his presentation.

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(1) 1 military pace = 0.75 m.

(2) The soil which Vauban refers to is Sparnacian clay which is from a level that corresponds with London clay, although it is less heavily overconsolidated. In Belgium it is called Boom clay and in France, Flanders clay. At Ypres it includes seams of glauconitic sand which in Vauban's time would almost certainly have been artesian.

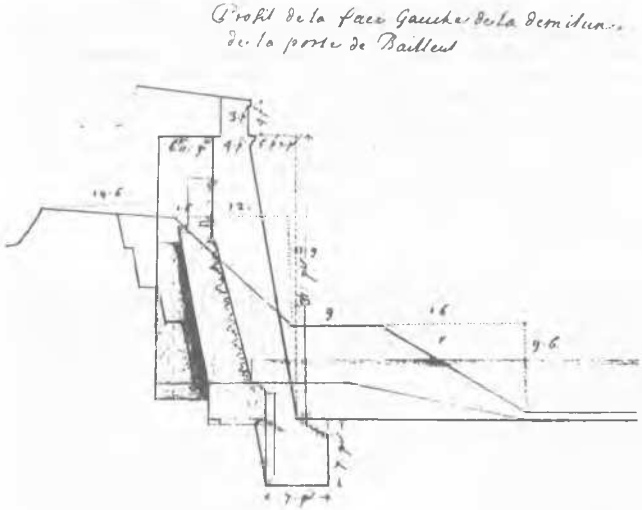

Fig. 89 - Underpinning of a wall at Ypres (end of 18th century). Archives Insp. Génie Vincennes.

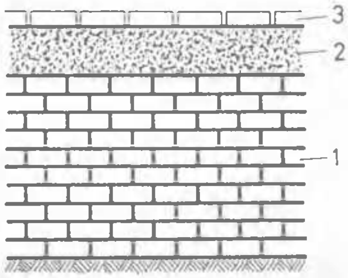

Fig. 90 - Paving in the Palace of Nabopalassar in Babylon.

VII - HIGHWAYS AND PAVING .

Transport by land was slower to develop than transport by water. Further, in antiquity the pavement construction used for the highways bore little relation to the intensity of traffic and frequently where the loads were light the pavement was thick, and vice versa. For example the floor of the Palace of Nabopalassar at Babylon (Fig. 90) comprised no less than ten layers of fired bricks (1) with bitumen joints, overlain by a layer of compacted earth mixed with bitumen (2) which in turn was covered by a layer of fired bricks with plaster jointing (3).

Similarly in the temple at Elephantine on Philae Island, in Upper Egypt, the floor

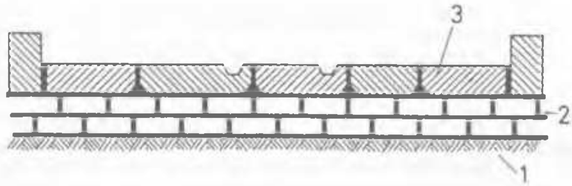

Fig. 91 - The Processional Way of the Temple of Ishtar at Ashur.

comprised fifteen layers, of which the upper layer was irregular, in opus incertum, with open joints symbolising the cracking of silt when dried in the sun.

On the other hand the major long-distance roads, and in particular the coastal roads linking Egypt, Syria and Mesopotamia were no more than simple tracks and travel by wheeled vehicle was difficult, therefore. Only the processional roads, along which the large statues of their divinities were carried, were paved.

Such was the case for the processional road for the temple of Ishtar at Ashur in Mesopotamia (Fig. 91). On a foundation of gravel two layers of fired bricks with bitumen joints were laid, over which a paving of slabs of red-veined gypsum (1) again with bitumen joints, was placed. The profile was concave so that the water drained to the centre; the joints between the gypsum slabs were very thin which prevented the bitumen bleeding out on a hot day. In fact, of course, the bitumen was really unnecessary for the quantity of traffic using the route. As can be seen the paving included two grooves spaced 0.70 m apart: these were not caused by wear but were cut in the stone in order to guide the carriages.

In the same way the Greeks overdesigned the sacred roads linking a city with a sanctuary, and those leading to the Oracle at Delphi, to the detriment of the long-distance routes. The form of construction used for the sacred roads was of two parallel lines of contiguous slabs in each of which a groove was cut for guiding the vehicles (Fig. 92). Often the rest of the road was not paved at all so that these routes have more in common with our modern-day railways than our roads. The spacing between the grooves varied from 1.38 to 1.44 m.

This standard width is probably related to the fact that the vehicles would have been drawn by two oxen, as compared to one at Ashur. The grooves were between 7 and 10 cm

(1) It might at first sight seem surprising that red-veined gypsum be used. In fact this type of gypsum is quite strong and not very soluble, and therefore suitable for a country with little rainfall.

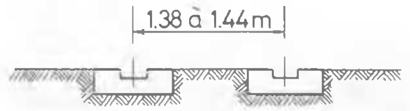

Fig. 92 - Simplified Greek road with two grooves cut into the stone, for guiding the carriages.

deep and between 20 and 22 cm wide. Only rarely did a road have two lines of grooves and it is not difficult to imagine the sort of confrontations that would have occurred when two carriages met. Perhaps it was on just such an occasion that Oedipus travelling on the sacred road that led to Delphi quarrelled with and killed a stranger, who turned out to be Laius, the father he had never known.

Apart from these operational difficulties, if the slabs were laid on a good well-compacted soil, these roads performed well under the light loading conditions that existed.

In their houses the flooring could certainly be described as functional, at least for festivities! Vitruvius provides the following description (Book VII, Chap. IV, Ed. Perrault 1664):

> "The Greek system does not displease me for it is not expensive and it displays many advantages. The soil is dug to a depth of two feet and the formation is compacted by a piling machine. A layer of mortar or cement is then laid, with a gradient towards two side channels. Above this a layer of charcoal is placed and well compacted. This in turn is overlain by a layer of lime and sand with cinders to a thickness of half a foot, which is carefully levelled. The surface is rubbed up with a grinding stone, which gives a dark coloured floor. It is very functional because anything that lands on it, as for example when one rinses the glasses or cleans out ones mouth, is soaked up, while those who serve at table can walk barefoot without being bothered by the cold."

In prehistoric times in Europe animals were used for labour very early on, and not only for agriculture: wheels dating from as far back as 2500 B.C. have been found, and close to Zurich a chariot 3.30 m long was uncovered. For this reason many roads built of logs were constructed in peaty ground in England, Switzerland, Germany and Italy, ahead of the equivalent developments by the Assyrians and the Greeks. However it was the Romans who made the greatest advances in the techniques of road building and produced roads that were not bettered until the 19th century.

Roman Roads

A Roman road was formed by firstly digging a broad trench, flanked by two ditches. The Roman engineers appreciated the importance of good drainage for the proper performance of a road: Statius, the poet laureate of the emperor Domitian, has left us a description of the site formation works for the Via Domitiana. This covers the excavation of the trenches, the diversion of streams, pumping by hand and the compaction of a layer of sand over the formation.

In its complete form, as laid down by Augustus for the construction of the Viae Militares, a Roman road comprised four layers:

- the two lower layers
  - above the formation the "statumen" which was 20 to 30 cm thick, being a layer of mortar over a layer of sand (1) (Fig. 93).
  - above this the "rudus" was between 30 and 50 cm of slabs and blocks of stone with cement mortar joints (2).
- the two upper layers
  - the layer beneath the surfacing was called the "nucleus" which comprised 30 to 50 cm of gravel and broken stones mixed with lime to form a kind of concrete (3).
  - the top layer was the "summum dorsum" (4) and could be of two forms, either stone slabs with cement mortar joints (Fig. 93 RHS) or a gravel concrete (LHS).

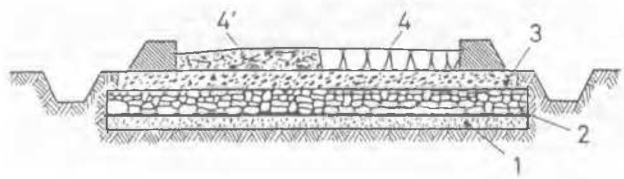

Fig. 93 - Cross section through a Roman road.

The same form of construction can still be used today if the summum dorsum is replaced by a bituminous surfacing and if gravel-cement or blast-furnace slag is used in the nucleus.

In total the pavement was 100 to 140 cm thick which equates with the Roman description of "a wall on its side". This thickness was arrived at through a long series of developments.

In the beginning their roads were very simple, lithostratos, following on from the Greeks where the technique was to spread quarry waste over the soil and compact it. As the road deteriorated the operation could be repeated. Rapid improvements followed the introduction of lime and natural pozzolanic soils, and even furnace slag (viae ferrae) of which there were many examples in Roman England.

The roads were built with a camber so that the water drained off to the ditches running along either side.

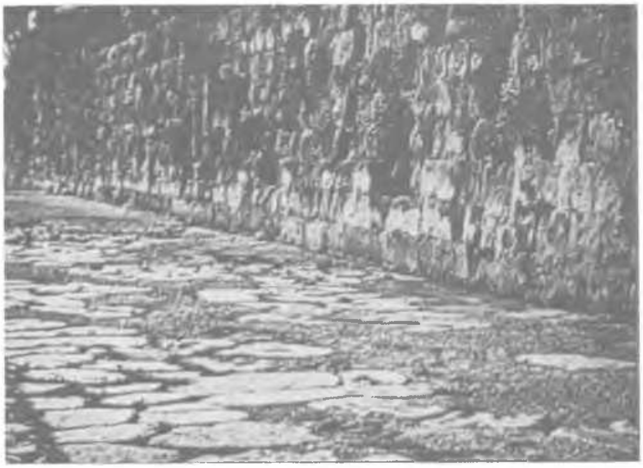

Fig. 94 - A paved Roman road: the Via Praenestina.

The length of primary roads built by the Romans reached a total of about 90 000 km which shows the industriousness and tenacity of this race. In addition some 200 000 km of secondary roads (viae vicinales) and tertiary roads with a single course of gravel were built. It was characteristic of the Roman engineers that they varied the form of construction both with the destination and with the ground conditions encountered.

Where the ground conditions were particularly poor wooden piles were sometimes used. Examples are found in the Via Ostiense that linked Rome and Ostia, and in the Medway Valley, close to Rochester, in England.

Because they preferred to build their roads straight, substantial earthworks were sometimes required in undulating country in order to provide a reasonable vertical alignment. On the Appian Way close to Teracina their is a cutting 36 m high and near Arricia a 43 m-high retaining wall.

In some cases tunnels were excavated, such as that on the Via Flaminia near Furlo at the site known to the Romans as Pietra Pertusa (pierced rock). The tunnel was constructed in 78 A.D., during the reign of Vespasian, and was 40 m long and 5 m high.

In the Danube gorge at Greben and Kasan the Romans had to build a cantilever wooden structure supported on steeply-sloping rock, in order to provide an adequate road for the legions.

However with the decline of the Roman Empire their techniques gradually fell into disuse: the nucleus disappeared, compaction was ignored; the sand blinding layer was left out and the statumen was only considered necessary in poor ground conditions.

We see that although transport by land developed rather more slowly than transport by water in the earliest times, the Romans developed the art of road building to such a degree as was not improved upon until the coming of the industrial age.

VIII - GEOTECHNICAL ENGINEERING AND WATER

1 - Theoretical research: Archimedes and Galileo

The most important name in antiquity in this field of research is that of Archimedes (287 to 212 B.C.). He studied at the School of Alexandria which since the 4th century B.C. had become the centre of Greek learning. His treatise 'On Floating Bodies' is the basis of our definition of submerged density. Besides his theoretical work Archimedes is also well known for the ingenious devices he invented such as the machine built to fire boulders at the Romans during the siege of Syracuse: this contraption could hurl a rock weighing 260 kg over a considerable distance. Nevertheless Archimedes did not put much store by his inventions and was much more interested in his mathematical research.

From the same period Philon of Byzantium, who wrote several treatises on pneumatics, established that air is compressible and water incompressible, ideas which are fundamental to our understanding of the behaviour of partially saturated soils.

From that time until Galileo (1562 - 1642) there were no significant theoretical advances. For instance the Roman Treatise on Aqueducts, dating from the end of the 1st century A.D., is a purely descriptive work, containing no theory: the Romans had only a rudimentary understanding of hydrodynamics. Pliny stated the principle that "a river continues upwards to its source" but he also believed that "if the water is transported a great distance it is necessary either to raise it or to lower it in order to conserve its driving force." The idea of loss of head increasing with velocity was not understood, therefore; Frontinus believed that water transported a great distance diminished in volume, thus reversing the advances in knowledge made by the School of Alexandria.

Galileo tried to further the research work of "divine Archimedes", as he called him. In a treatise entitled "Discourse on Things That

Float" he considered the behaviour of objects of the same density but of different shapes that either sank or floated in water, and noted how some objects sitting on the bottom were displaced when the water was agitated and others not.

2 - Underground works

2-1 - Drains

The development of the first settlements saw the beginnings of agriculture and a requirement for drainage and for irrigation: this occurred at the beginning of the Neolithic period as we have already seen (section II-4). In particular the inhabitants of the Middle East appreciated the importance of effective drains, both vertical and horizontal. We have already given examples of vertical drains, while horizontal drains were needed in the alluvial plains where silt was being deposited continually.

It is hardly surprising that the successful reclamation of submerged marshy land using horizontal drains was not achieved on a large scale until the 16th century, simultaneously in Holland and in Italy. One of the most successful engineers in Holland was Stevin who in 1584 took out a patent for a pump that incorporated a bucket-wheel and was driven by a windmill, which was used for draining the polders. In Italy, where the Roman methods had been in disuse for so long, similar techniques to those of the Dutch were employed by the citizens of Venice, Verona and Florence, to drain the Po valley and make the soil cultivable.

The methods used in the Fens in England and in the Saintonge region of France derived from the Dutch experience (L. E. Harris 1954).

2-2 - Capture and the underground transport of water

The underground transport of water is often necessary for irrigation in a country that is hot and has a high rate of evaporation and a low rainfall. There are two important techniques: artesian wells and qanats.

2-3 - Artesian wells

The artesian well was invented by the Egyptians who used them for creating an oasis. According to Beadnell (1909) a square timbered pit, about 1.80 m x 1.80 m, is dug to the maximum depth possible. A wooden casing is then inserted, which may consist of hollowed trunks of palms joined end to end, and the volume between the casing and the timbering is backfilled. The excavation is then continued using metal rods (Fig. 95) until the aquifer is reached. Obviously this method could take some considerable time and is only feasible when the aquifer is at a shallow depth.

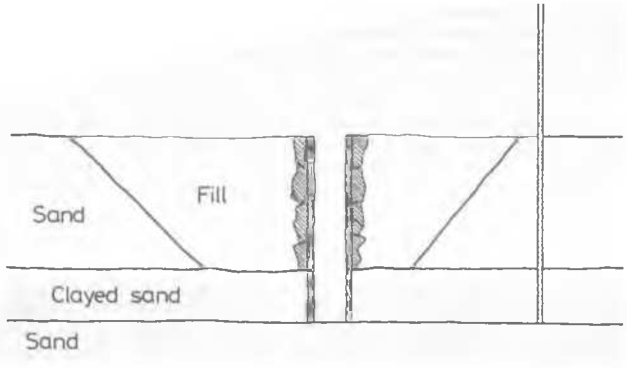

Fig. 95 - Egyptian method of excavating an artesian well, based on the description by Beadnell (1909).

2-4 - Qanats

The Persians exploited the sources of water found in the scree and rubble at the foot of a chain of mountains by excavating tunnels that led the water away at a gentle slope underground. The purpose of these qanats was to preserve the freshness of the water and to prevent evaporation. The lines of the qanats are easy to spot from the air as they are marked by a shaft every 50 m or so that was used for evacuating the soil and for ventilation. Their maintenance posed problems: Adaluirari (911 to 889 B.C.) mentions a qanat that had to be re-excavated, which had not produced water for 30 years.

2-5 - Siphons

The Greeks also transported water underground and they made use of the siphon. One in particular, built at Pergamum in the 2nd century B.C., was subjected to a maximum pressure of 20 atmospheres (2MPa). For such a pressure it would not have been possible to use earthenware, so the pipes must have been of lead or bronze.

Thanks to Herodotus we also possess details of the water-supply system of the town of Samos. It was built in the 6th century B.C. under the supervision of Eupalinos and included a tunnel and a pipeline supported on stone pillars. The tunnel was about 1 000 m long and of square section 8 ft by 8 ft and fully lined. Excavation for the tunnel began from both ends simultaneously, but apparently there was a setting-out error as there is a substantial kink in the alignment near the middle. Similarly it seems that the longitudinal fall was insufficient as additional excavation was required on one side of the tunnel.

Again in Herodotus we read that Thales of Miletus, whom Herodotus considered as one of the men most gifted in the "mechanical arts", excavated a tunnel in 558 B.C. to divert the Halys River and facilitate the passage of Croesus' army. Clearly the

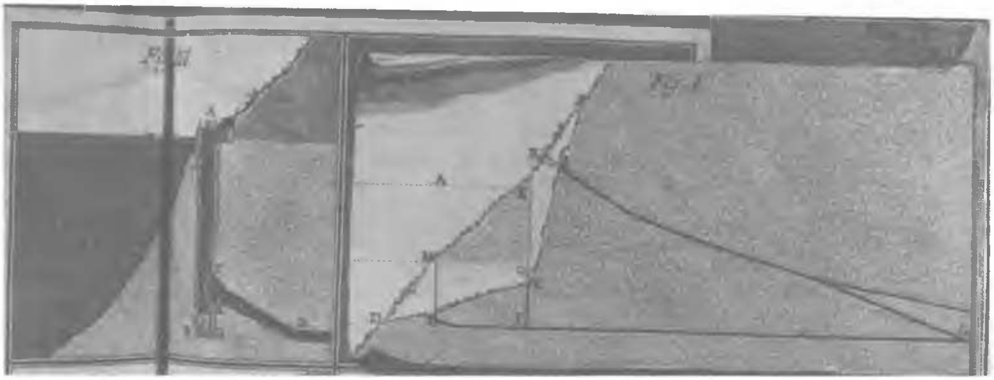

Fig 96 - Lake Albano. Project for preventing the lake over-filling. From an engraving by Piranesi.

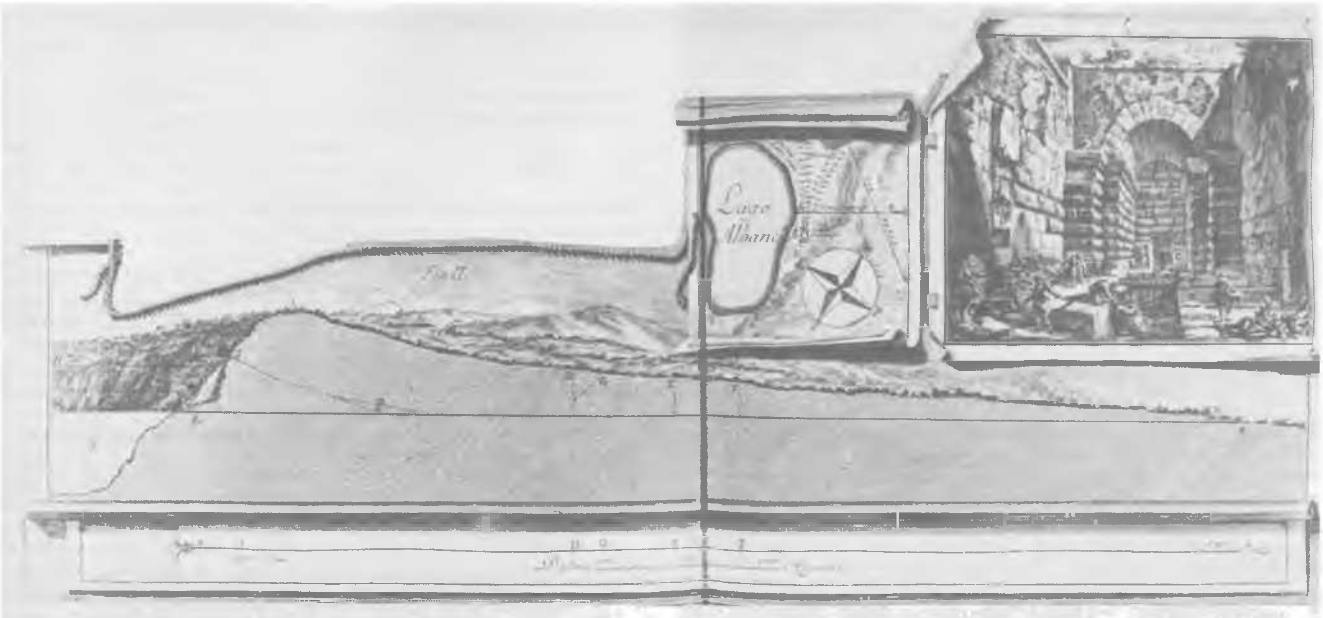

Fig. 97 - Lake Albano. Below - profile of the 1.425 m dia. adit.
Above centre - location of the lake near Castel Gondolfo.
Above RHS - the outfall.
From an engraving by Piranesi.

Greeks were not hesitant in undertaking such projects.

2-6 - Roman aqueducts

The Romans preferred to transport their water at surface level (aqueducts, canals) even though the water supplying the city of Rome came from as far away as 100 km. Nevertheless they did excavate some tunnels, one notable example of which is the overflow for Lake Albano, as illustrated in Piranesi's engravings (Figs. 96 and 97).

Archaeologists have discovered a few underground canals excavated by the Romans through rock, that were not provided with any form of lining (e.g. sections of the Nasseur-Allah aqueducts between Kairouan and Gafsa). Usually however an arch roof and walls were built and a stone-lined drain, the cross section varying from 0.40 to 0.60 m between the walls with a height of between 1.20 and 1.50 m. The Romans used formwork for shaping the arch roofs but never employed ribs.

The Cloaca Maxima, the great sewer of Rome, was, in places, as large as 3.2 m wide and 4.2 m high. In fact it was originally built as an open ditch but was covered over in the 3rd century.

The Romans appreciated equally the importance of providing sufficient support to their tunnels and of incorporating erosion protection. This is illustrated by the following account of the siege of Marseilles (Vitruvius Book X, Chap. XXII): "Similarly when Marseilles was besieged, and the enemy had made more than thirty mines; the Marseillois suspecting it, lowered the depth of the ditch which encompassed the wall, so that the apertures of all the mines were discovered. In those places, however, where there was no ditch, they excavated a large space within the walls, of great length and breadth, opposite to the direction of the mine, which they filled with water from wells and from the sea; so that when the mouths of the mine opened to the city, the water rushed in with great violence, and threw down the struts, overwhelming all those within it with the quantity of water introduced, and the falling in of the mine."

Like the Greeks the Romans did not hesitate in undertaking geotechnical and hydrogeological projects on a grand scale, as witnessed by the following excerpt from Tacitus (Annals, Book XII, 56 and 57):

56.1 "A tunnel through the mountain between the Fucine Lake and the river Liri had now been completed (1). To enable a large crowd to see this impressive achievement a naval battle was staged on the lake itself. Claudius equipped warships manned with nineteen thousand combatants, surrounding them with a circle of rafts to prevent their escape. Enough space in the middle, however, was left for energetic rowing, skillful steering, charging, and all the incidents of a sea battle. On the rafts were stationed double companies of the Guard and other units, behind ramparts from which they could shoot catapults and stone-throwers. The rest of the lake was covered with the decked ships of the marines.

The coast, the slopes, and the hill-tops were thronged like a theatre by innumerable spectators, who had come from the neighbouring towns and even from Rome itself - to see the show or pay respects to the emperor. Claudius presided in a splendid military cloak, with Agrippina in a mantle of cloth of gold. Though the fighters were criminals they fought like brave men. (2) After much blood-letting they were spared extermination."

57.1 "After the display, the waterway was opened. But careless construction became evident. The tunnel had not been sunk to the bottom of the lake or even halfway down. So time had to be allowed for the deepening of the channel. A second crowd was assembled, this time to witness an infantry battle fought by gladiators on pontoons. But, to the horror of banqueters near the lake's outlet, the force of the out-rushing water swept away everything in the vicinity - and the crash and roar caused shock and terror even farther afield. Agrippina took advantage of the emperor's alarm to accuse Narcissus, the controller of the project, of illicit profits. He retorted by assailing her dictatorial, feminine excess of ambition."

In fact it is probable that the Imperial Court was nearly the victim of a shock wave caused by the trapped air rushing out: Narcissus had failed simply to provide a balancing ventilation shaft.

3 - Dykes

We have already discussed the dykes of Mesopotamia in section III - 4 - 2.

The first treatise on dykes in low lying land built on compressible soils was written by the Dutchman Andries Vierlingh and is entitled "Tractaet van dyckagie." It draws on the experience gained in Holland in building dykes both for protection from the sea and for reclaiming marshy land. He distinguishes between three types of dyke:

1) the slikkerdijk comprising a core of earth with a clay covering to the side slopes and a protection layer of bundles of straw or willow.

2) the wierdijk for less exposed areas, where the protection layer was of seaweed.

3) the rietdijk for the least severe conditions, where bundles of reeds replaced the seaweed.

In other words what distinguishes between the three types of dyke is, in modern terminology, the plant geotextile chosen.

At a later date more effective means of protection were used such as palisades of piles and, later still, the "krebbingen" which consisted of two lines of small wooden piles a few feet apart, the gap being filled with fascines tied to the piles with straw binding: stone protection was found to be too expensive.

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(1)Ch.56 appears to refer to 51 A.D. and ch. 57 to 52 A.D. The mountain is Mt. Salviano between the Celano Lake and the river Garigliano, linked by a canal 4.5km long. Planned by Caesar the works took 11 years to build with a labour force of 30 000 men: cf Suetonius, Caesar 44,3; Claudius, 20.2, Pliny H.N. XXXVI, 124 Dion LX, 11,5. The lake was not drained until the 19th century.

(2) Suetonius, Claudius, 21, 6, gives another version.

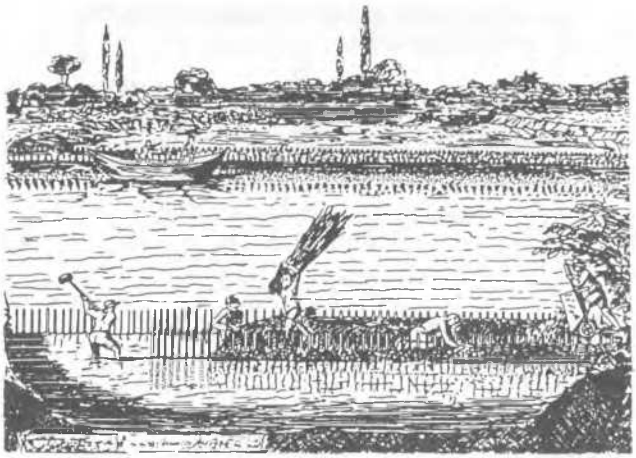


Fig. 98 - Construction of dykes on a river, by Meijer in 1683, using krebbingen.

In Italy, contemporary with Vierlingh, the most distinguished engineer in this field was the Florentine Antonio Lupicini (1530-98). In 1587 he published his "Discorso sopre i ripari del Po e d'altri fiumi che hanno gl'arigini di terra posticcia" (Discourse on the protection works in the form of earth levees built on the banks of the Po and other rivers). The levees were built of layers of compacted earth, 3 m thick, alternating with layers of straw. The dykes had a width at the base equal to three times the height, so the side slopes were approximately 1(v): 1.5(h), which might appear to be comparatively steep but turns out to be acceptable due to the beneficial reinforcing effect of the straw. Erosion protection was provided in the form of wooden logs placed at a spacing of 1.20 m, linked laterally and fixed using pieces of willow. This formed a sort of mattress that extended from the low-water level up to the limit of the erosion. A layer of stones was placed over this mattress.

At a later date the Dutchman Janszoon Meijer, at the request of Pope Innocent XI, undertook a substantial programme of protection works for a number of Italy's rivers, making extensive use of wooden piles and fascines (Fig. 98) i.e. the krebbingen discussed above.

4 - Canals

The history of ancient canals has been superbly set down by our colleague A. W. Skempton in the encyclopaedia "A History of Technology" (1957). Here we will only consider some of the geotechnical and hydrogeological aspects.

The canal has a noble ancestry that dates right back through antiquity; in Egypt the first district governors of the Old Kingdom were given the title "Diggers of Canals"; a whole hierarchy of engineers (hyper-architecton) existed to oversee the supervision of their construction and maintenance. Nevertheless with time the political outlook changed and less emphasis was placed on maintenance so that today not a single canal from ancient Mesopotamia or Egypt has survived (1), despite their size: some were large enough to accommodate two triremes rowing side by side (Herodotus II, 158). Strabo (XVII, 25-26) talks of "A width of one hundred cubits" as does Pliny (XV, 33) who gives a figure for the depth of 40 feet. However no details are given of the side slopes.

The Grand Canal in China, completed in 610 A.D., is nearly 1 000 km long and is without locks. Much of the work that resulted in the construction of this canal was begun in 215 B.C.

At the same time in Europe little progress had been made in developing modes of transport by water and this remained the case until the invention of the mitre-gate by Leonardo da Vinci in 1497, which paved the way for the construction of the first locks. Some of the earliest examples came from Flanders such as that at Boesinghe discussed earlier. The invention spread rapidly to England, Germany and Sweden. At this stage the canals were still relatively small. The great age of canal building in Europe opened with the construction of two major canals in France during the Renaissance, the one linking the Seine and the Loire between Montargis and Briare, the other the Canal Royal du Languedoc (also known as the Canal du Midi).

The Languedoc canal (1666-81) was built "to link the two seas, the Atlantic Ocean and the Mediterranean", and represents an outstanding achievement. The canal begins at Toulouse (altitude 130 m) which is connected to the Atlantic via the Garonne river. From Toulouse via 32 locks it rises 63 m over a distance of 32 miles to its maximum altitude. It then remains level for 3 miles, before descending over a distance of 115 miles, through 74 locks, to the port of Sète on the Mediterranean (Fig. 99).

At the height of the construction works 8 000 men were employed on the project. The canal was designed by Riquet who also supervised its construction, under the watchful eye of Colbert, Louis XIV's Prime Minister. Riquet was to die at the age of 76, seven months before completion of the project. In debt, he had written the following in a letter to Colbert: "I look upon my canal as the dearest of my children: in fact I have two daughters who are still living with me and I hope that

(1) Including the canal joining the Nile to the Red Sea, which was completed by Darius around 500 B.C.

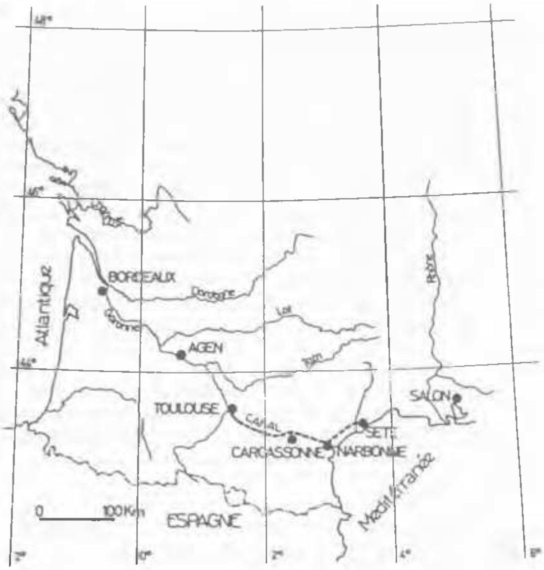


Fig. 99 - Simplified map showing the route of the canal.

they will stay a while longer so that I can use the money that should be going to their dowries on the project".

The construction works benefitted greatly from the experience gained on the Montargis-Briare canal. This latter project was begun in 1604 and finished in 1642. From Montargis it rises about 80 m: the drop in head in the locks was about 3 m, or exceptionally 4 m, which is similar to that in the locks on the Canal du Midi.

Of the developments that took place during construction the changes in the profile of the canal and in the design of the locks are interesting from a geotechnical point of view.

At the preliminary design stage, in 1664, the side slopes proposed for the canal profile were over-optimistic. The width of the floor of the canal was selected as 6 toises (1) while the width at the surface of the water was 8 toises for a depth of water of 2 toises. This implies side slopes of 1(h):2(v). However the figures quoted in the contract documents are, respectively, 5 toises 2 pieds, 8 toises and 1 toise 3 pieds i.e. side slopes of 1(h):1.17(v), which is still quite steep. This was the profile used for the first section built, the 12 km from Toulouse to Castanet. However for the rest of the canal Riquet asked Colbert that the side slopes be reduced to 1(h):0.4(v) (Fig. 100). In his letter to Colbert dated

Fig. 100 - Final cross-section of the canal (after Froidour p.31).

27 May 1670 he justifies the change in claiming that "the canal will be more solid, convenient, simpler and more elegant".

However it is likely that one of the real reasons was the instability of the side slopes because Froidour remarks in a letter dated 1672, rediscovered by Adgé (1984), that before the change was made slips were occurring everywhere. Nevertheless Riquet could have made use of a clause in the contract documents which stated that: "If the nature of the soil encountered requires a wide embankment the width of the canal at the surface of the water shall be increased to that which should prove necessary ..." That is, he should have adapted the design to suit the ground conditions.

In fact the ground conditions varied greatly. In the central section the soils were better (molasse, calcareous breccia, limestone) than at either end (clayey or clayey/sandy alluvium around Toulouse, marshy soils at the other end), that is they went from one extreme to the other.

In addition it appears that Riquet's surveyors made a setting-out error over the Toulouse-Castanet section so that the canal was wider than originally provided for. Bearing in mind that Riquet was under close surveillance, by making the side slopes shallower on the next section he was able to avoid a discontinuity in the width of the canal. With time the side slopes on the first section flattened out naturally.

Vauban looked at possible improvements to the canal including altering the alignment so that the exit at the Mediterranean end was at L'Etang de Bouc, considerably further to the east. In 1689, in his "Oisivetés", he proposed to widen the floor of the canal to 10 toises, in order to take ships of 200 to 300 tons displacement. The side slopes proposed were 1(h):0.5(v).

In the design stage, in order to get around the problem of erosion and silting up that might be caused by the numerous streams and rivers that crossed the line of the canal, Riquet proposed the construction of a number of aqueducts. In fact only the aqueducts of Repudre (Fig. 101), l'Aiguille and Jouare were built at this stage.

Nevertheless in 1684 Vauban was commissioned to make a study of the condition of the canal: 4 000 probe holes were carried out

(1) 1 toise = 1.96 m
6 pieds = 1 toise

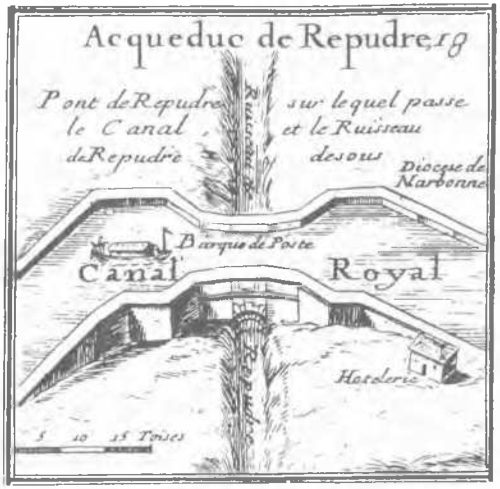


Fig. 101 - The aqueduct at Répudre (Carte de Nolin 1697).

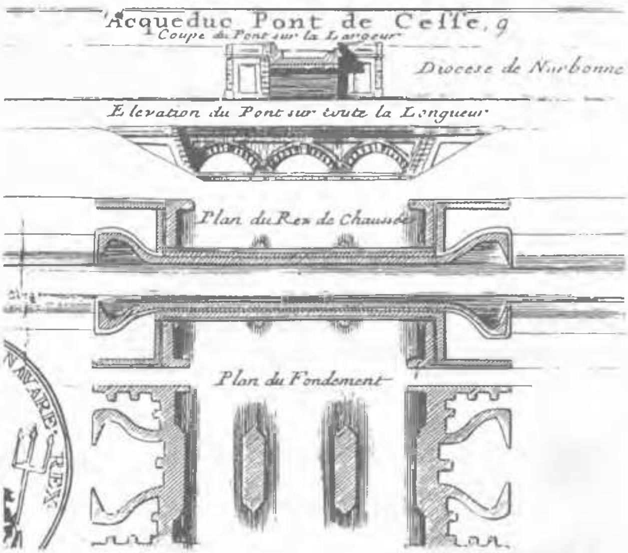


Fig. 102 - Section, elevation and plan view of the aqueduct over the Cesse (Carte de Nolin, 1697).

which showed that the canal had become seriously silted up.

In his report dated 4 March 1686 Vauban proposed the construction of 22 aqueducts, although this figure was later reduced to 14. Vauban was a much more daring engineer than Riquet and rather than follow the contours up every little river valley he proposed the construction of long embankments with aqueducts to allow the rivers to pass beneath the canal. The embankment and aqueduct over the Cesse (Fig. 102) is over 500 m long. The material used for the embankments was a compacted puddle clay that had to be sufficiently impermeable to retain the water but sufficiently strong to be stable over a considerable height. It was not always possible to satisfy these two conditions in the long term: for instance nearly one hundred years later in 1766, the embankment leading up to the aqueduct at Saisse collapsed. The fill was 10,50 m high and the side slopes now stand at 1 (v) : 3 (h) but were certainly steeper originally, although no details have been found.

The first locks to be built were those at Toulouse; the lateral walls were straight and of brick (Fig. 103 LHS) with a rectangular section 6 pieds thick (1.95 m); the tallest were about 7 m high. Some of the locks (including the Garonne lock) were founded on piles, due to the compressible nature of the soils. Shortly after completion of the Minimes lock (Adgé 1984) one of the lateral walls began to lean out of plumb. It was believed that this was because, one month after the wall was built, when backfilling began, the mortar between the bricks had still not set. However to me it seems quite possible that earth pressure from an embankment on soft ground could cause a brick wall founded on piles to overturn where the thickness to height ratio is only 1:4.

Riquet had to allay any fears that Colbert might have had with regard to stability, and in 1670 he decided to demolish the five locks at Toulouse and to re-build them to a different design. Three of them, including the Garonne and Minimes locks, became double locks, thereby reducing the height of the walls. In addition, in order to please Colbert who had asked the advice of some masons, Riquet included some short counterforts behind the lateral walls (Fig. 103 centre). However, as can be seen, they were so small that they could not possibly have had any significant effect. As a second design change it was decided to curve the lateral walls (Fig. 103 RHS)) as well as provide them with a slight batter, thus giving them their peculiar shape.

Several multiple locks were built including one tier of eight locks (that at Fonserannes) (Fig. 104).

From the very beginning Riquet appreciated that the success of the whole project depended on a reliable water supply and so the construction works commenced with the St. Ferréol dam (Fig. 105), near Maurouze. This structure is 31.50 m high at the widest point and was built of earth and stonework. The reservoir behind has a capacity of 250 million^3 and the dam is still in good condition today, 300 years after completion.

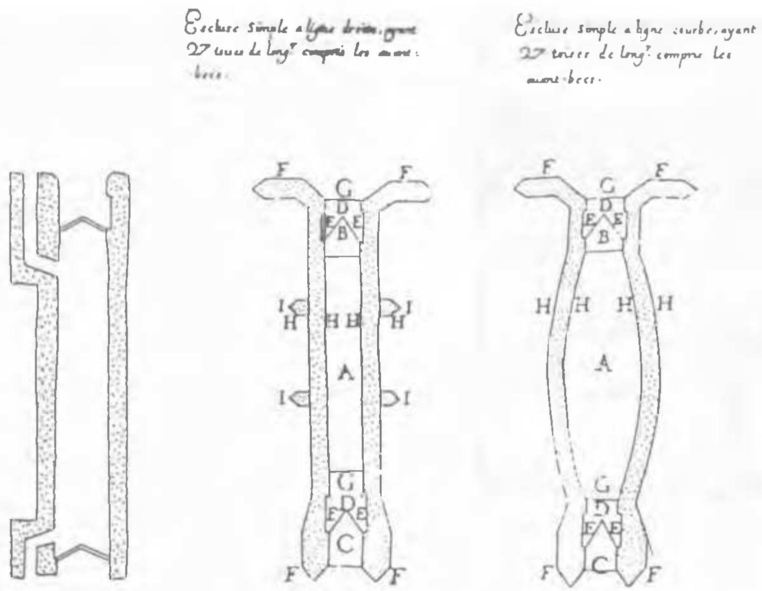


Fig. 103 - LHS - the original design, after Andreossy (1666).
Centre - the first design change, incorporating short counterforts.
RHS - the final design (after Froidour p. 31).

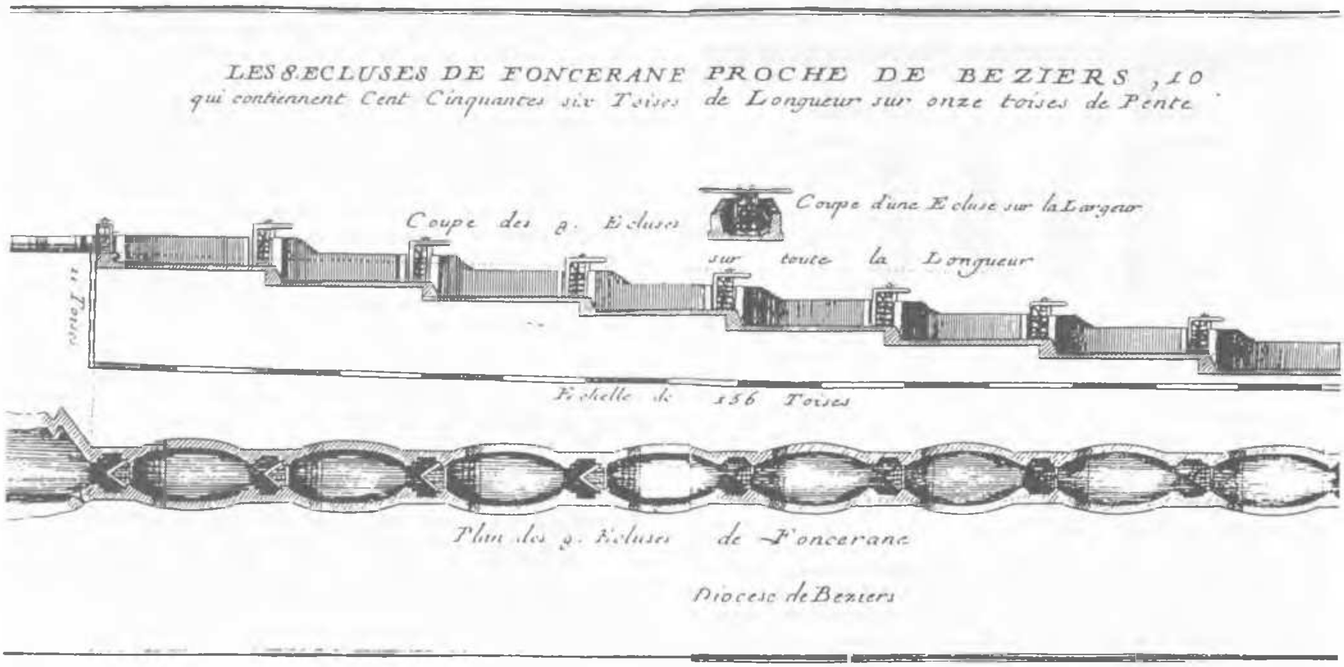


Fig. 104 - Section and plan view of the Fonserannes locks in the 17th century (Carte de Nolin, 1697).

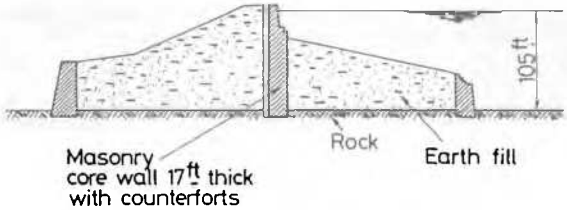


Fig. 105 - Canal du Languedoc - Section through the St. Ferréol dam (1667-1671) at the point of maximum thickness.

IX - UNDERGROUND STRUCTURES FOR INDUSTRY AND AS DWELLINGS.

1 - Industry

In the Near East the Copper Age began around 4000 B.C., followed by the Bronze Age around 2500 B.C. and the Iron Age around 1400 B.C. The excavations for extracting the ore soon became sufficiently large that they required some form of support. They were not the first such excavations as, earlier, Neolithic man had dug for flint for shaping into tools: the instruments used for digging were animal bones (Fig. 106) and the discovery of the

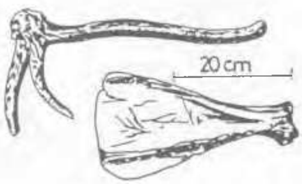


Fig. 106 - The antlers of a stag used as a scraping tool and the scapula of a cow used as a spade. (Flint mines at Harrow Hill near Worthing, Sussex, England).

Fig. 107 - Skeleton of a miner caught by a tunnel collapse while digging for flint with a scraping tool (Obourg, Belgium).

Fig. 108 - Reconstruction of a fire in a copper mine in Mitterberg, Tirol, in order to break up the rock. (1600 to 800 B.C.).

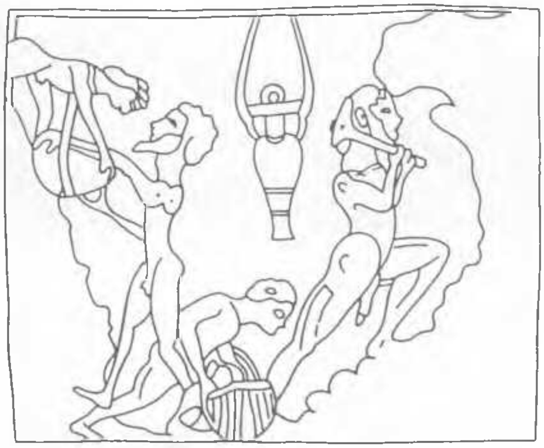


Fig. 109 - Greek miners. The ore excavated was removed in baskets. Note the amphora used for lighting.

skeleton of a miner with his digging tool (Fig. 107) shows that sometimes the tunnels collapsed.

At the beginning of the Copper Age the tunnels were usually dug in the side of a hill, with a slight positive gradient thereby facilitating drainage and the removal of spoil. Later, in order to exploit the richest deposits, it was necessary to follow the local geology and to lengthen the tunnels and deepen the

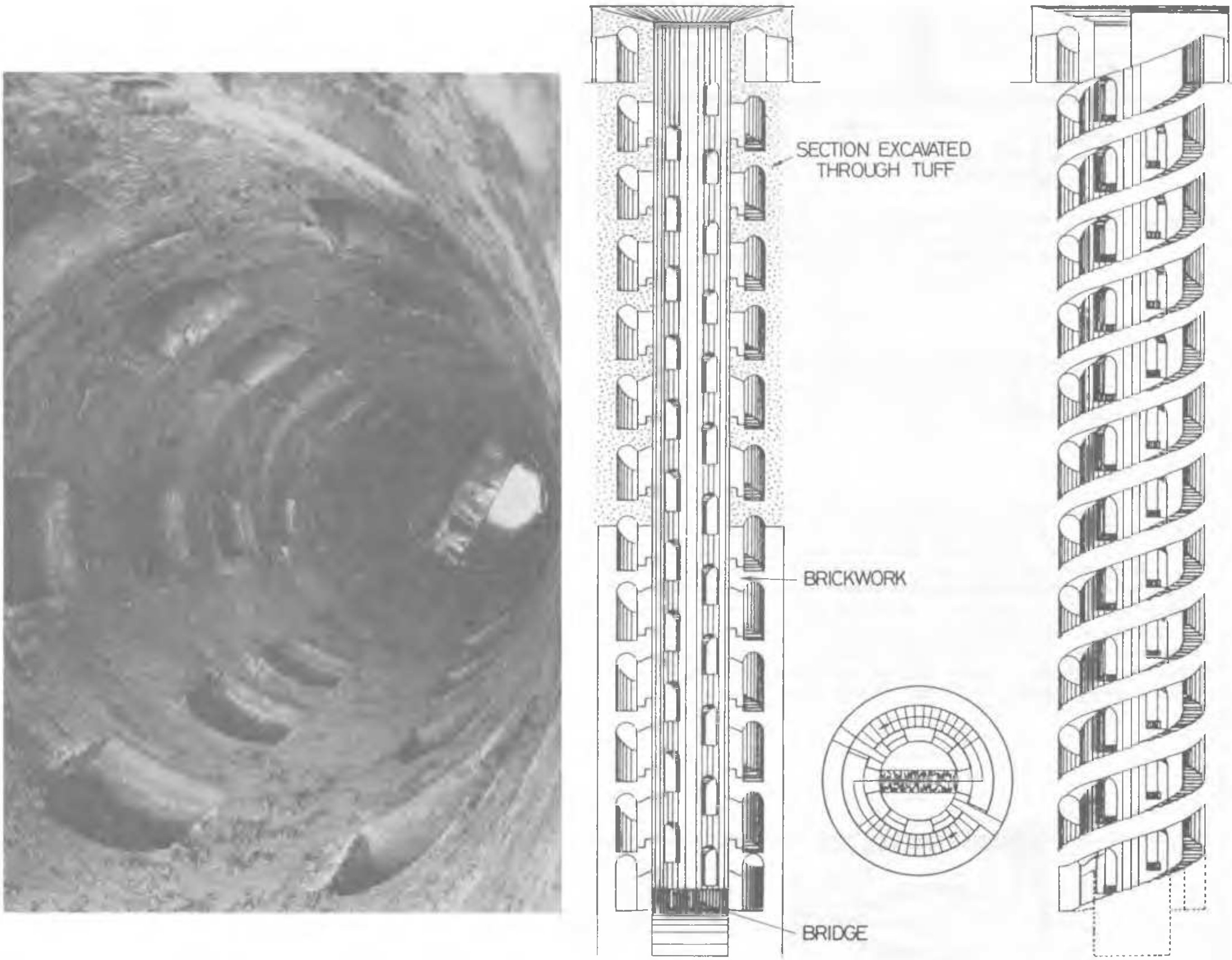


Fig. 110 - The shaft at Orvieto built by the Italian military engineer de Sangallo in 1530.

shafts. To break up rock the method used was to light a fire to heat the rock and then to suddenly quench it with water to make the rock crack (Fig. 108). Nevertheless the methods of excavation and lighting used were rather rudimentary if we are to believe Fig. 109.

A description of the shape of the shafts and adits is given by Pliny (Natural History: 33-36-37). The shafts were rectangular, the length of the short side varying between 1.25 and 1.40 m and of the long side between 1.50 and 1.90 m. They could be as deep as 50 m or sometimes even 100 m. These dimensions of the cross section would be internal because in Palladius Book IX we read: "Their width should be eight feet of which the stonework will take two. If there is any danger of collapse the earth should be supported by straight planks which are themselves supported by cross struts, in order that the earth does not collapse on the workers." Some mines contained an enormous number of shafts: for instance at Leurion there are nearly 200.

Concrete was not used until much later, during the Renaissance, to build large cellular shafts of circular cross section (Fig. 110).

Deep circular wells of large cross-section did not appear until the Renaissance. The well at Orvieto was built by Antonio de Sangallo over the period 1527-1537 at the request of Pope Clement VII who lived in the town at that time, in order to provide the town with water in case of siege. The well is 58 m deep and was excavated through a volcanic tuff, then clay, beneath which water was found.

The walls of the well form a hollow cylindrical ring, of internal diameter 4.70 m and external diameter 9.07 m, that contain two independent spiral staircases, one for the descent of the citizens and their beasts of burden, and one for their ascent. A total of 70 windows were provided in the inner wall of the well.

Prior to the Iron Age saws of copper, without teeth, were used in conjunction with an abrasive material (corundum powder, etc.). The excavated material was carried out by hand on flat wooden trays, and the lighting, where provided, was by means of resin torches or animal skin soaked in fat, although according to Pliny the miners often worked in darkness (Natural History 33.70). The Roman tried to provide some form of ventilation, but they were not terribly successful. Strabo gives a description of the atmosphere in the arsenic mines of Pinolisa at Pontus:

> "The air in the mine was noxious: it was difficult to stand the smell of the mineral, and anyone working in that mine was promised an early death."

Fig. 111 - Techniques involved in the excavation of a mine, after Agricola (1556). Note the winches and the trolleys with four wheels.

The most important work on mining and metallurgy from the Middle Ages is the De re metallica (1556) of Georg Bauer (1494-1555), who was more commonly known as Georgius Agricola. Fig. 111 is a reproduction of an engraving from his book. It shows three shafts of dimensions 3 m xlm: the material was transported in trolleys with four wheels and the excavations were kept dry by means of hydraulic pumps. In addiion there were shafts provided for ventilation, or as an escape route. At the top of the shaft wa's a chimney in the shape of a truncated cone. The air in the mine could be made to circulate by lighting a fire at the base of the shaft.

2 - Dwellings

In this section we shall treat any natural formations used as dwellings as being outside our subject and concentrate on man-made structures. Nevertheless two 17th century books on caves are of interest: the first "Mundus subterraneus" (or "the underground world) was written in 1665 by Father Kircher, and the second, written by J. Gafford in 1654, bears the rather long title of "The underground world, or an historical and physical description of the most beautiful caves and the Earth's most exceptional grottos, and in general all the most famous caverns, cavities and underground passages and all the interesting things that are found therein."

2-1 Vertical holes

One of the earliest forms of dwelling is a simple circular hole in the ground, developed in those areas where the ground conditions were suitable, as soon as man acquired the ability to dig. Fig. 112 shows an example from China excavated in loess.

In the Neolithic the form of the dwellings evolved to that shown in Fig. 113.

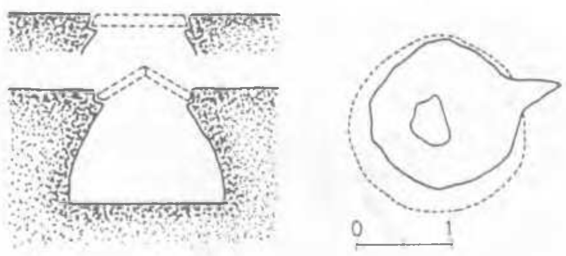


Fig. 112 - Plan view of a circular underground dwelling in Jianxi, Henan province, China.

1 - perimeter of excavation at ground level
2 - perimeter of excavation at floor level
3 - location of fireplace

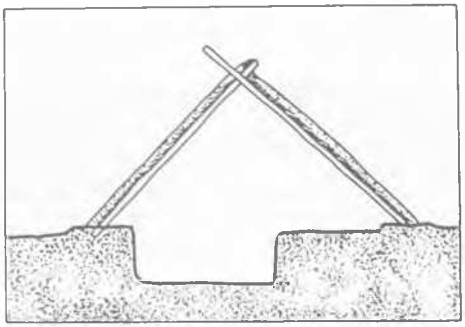


Fig. 113 - Dwelling of semi-nomads of Outer Mongolia.

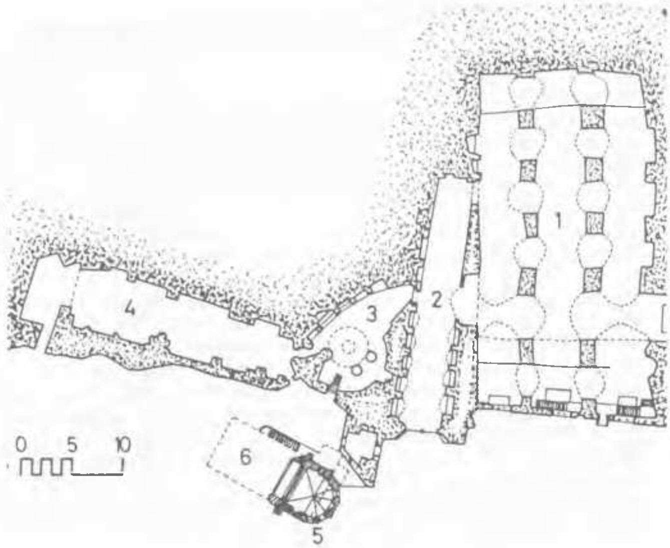


Fig. 116 - The Eglise monolithe de Saint-Emilion (Gironde region of France).

1. Eglise monolithe (church)(9th to 12th century)
2. Original church (8th century)
3. Charnel house (9th century)
4. Catacombs (11th century)
5. Chapel of the Trinity (13th century)
6. Hermitage of Saint-Emilion (8th century)

2-2 Horizontal excavation

In general however underground buildings were formed by excavating horizontally in the side of a hill or a cliff: the technique was used for dwellings and also for temples or other religious structures in different countries, including Egypt (Fig. 114), India (Fig. 115) and France (Fig. 116).

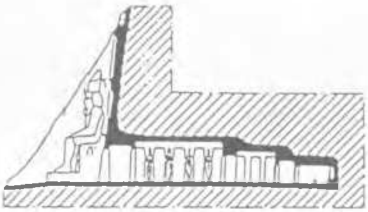


Fig. 114 Tomb of Ramesses II at Abu Simbel, Egypt. Section.

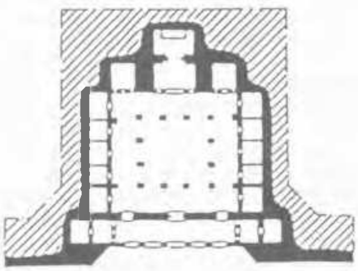


Fig. 115 The Ajanta Caves vihara in India. Plan View.

Nevertheless rupestrian architecture (i.e. excavated in rock whether for a dwelling or for religious purposes) is only really of interest to the geotechnical engineer if he knows details of the dimensions of the buildings, of the properties of the rock, of the seismology of the area, the thickness of the cover, etc.... With so many examples to choose from I shall have to limit myself to a few general comments.

In India there are a number of monasteries excavated in rock, which is often a hard granite: in these "caityas" the rooms could be as large as 12 m x 30 m. Many of the temples have several entrances. The Indian "silpins" developed the techniques of excavation in rock to a high level of sophistication: the excavation for the Ellora Caves temple (8th century), which covers a larger plan area than the Parthenon, was finished in less time than it would have taken to build an equivalent masonry structure. In China many underground structures were excavated in the loess. On the other hand in Central Asia, where the rock is more friable than in India and where earthquakes are relatively frequent, the dimensions of the underground chambers were more modest. For the same reasons, but to a greater degree, it appears that there have never been any troglodyte dwellings in Japan.

2-3 - Burial chambers of the Pharaohs

Much more rewarding is the study of the methods of construction and of the long-term behaviour of the burial chambers built by the Pharaohs. These fall into two categories:

1) those in or beneath a pyramid.
2) those excavated in rock (such as in the Valley of the Kings) and not associated with a pyramid.

2-3-1 - Burial chambers associated with pyramids

The Egyptians encountered great difficulties with the thrust acting on the roof and walls of the burial chamber and despite experimenting with different layouts no standard technique emerged that was entirely successful. We will look at a few examples in chronological order.

The earliest solution (as used at Saqqarah, Sekhemkhet and Zawiyet el-Aryan) was to locate the burial chamber and descending corridor in the strata beneath the pyramid, which worked well provided that the material was rock and that there was sufficient cover to the roof.

At Meidum the burial chamber was embedded in the underlying soil with the side walls standing out just 1 m above ground level. The width of the chamber was only 2.55 m and the roof was a corbel vault, the only form of vault known to the Egyptians. Whereas at Meidum there were no significant deformations this is not true of the Bent Pyramid, Dahshur South, founded on stiff clay. Snefrou built a first chamber founded in the underlying soil, considerably larger than the burial chamber at Meidum. Under the action of the thrust on the roof and on the walls, transmitted through the soil, the roof was displaced vertically 30 cm. A second burial chamber located in the core of the pyramid has a width of 5.30 m, with side walls 3.50 m high and a corbel roof rising to a height of 13 m. Due to the inwards movements of the side walls large cedar-wood struts had to be installed which are still in place today. Dahshur South, therefore, provides the best example of difficulties encountered in building a heavy rock-fill structure on a deformable soil, and in constructing a large chamber either in the structure itself, or in the underlying soil at a shallow depth.

The twin burial chambers beneath the North Stone Pyramid at Dahshur are approximately at ground level but they are not so large (3.50 m width) and rock underlies the pyramid, which explains why they have not undergone any severe deformation.

The pyramid of Cheops, however, shows how undecided the Egyptians were in locating the burial chamber, for there exists an uncompleted alcove in the rock beneath the pyramid (2) (Fig. 117) reached by a narrow corridor (1 m wide), while the final location

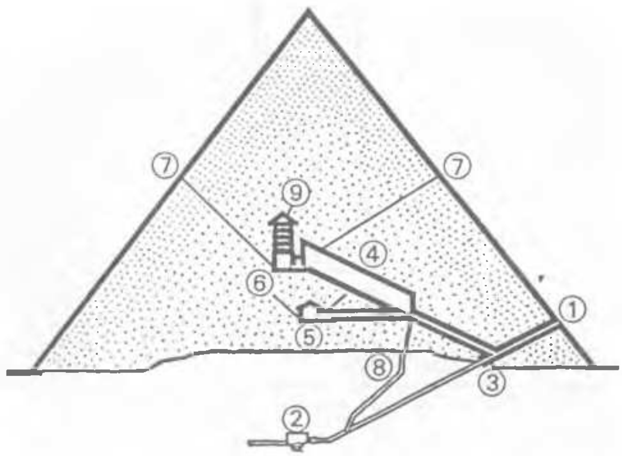


Fig. 117 - Section through the Great Pyramid of Cheops, facing west after Colonel H. Vyse.

1 - Entrance to the descending corridor
2 - Unfinished chamber
3 - Descending corridor
4 - Grand Gallery
5 - Queen's Chamber
6 - Unfinished rectangular apertures
7 - Shafts leading to the King's Chamber
8 - Shaft leading to the descending corridor
9 - King's Chamber

chosen (9) is in the heart of the pyramid. The most remarkable of the various chambers inside the Great Pyramid is the Grand Gallery (4) which is 46 m long and 7.40 m wide at the base. The side walls form a corbel vault of polished limestone, stepping in by 9 cm for each rise of 2.25 m (Fig. 118). It is likely that successive levels of the Grand Gallery were built at the same time as the corresponding levels of the bulk of the pyramid, with temporary props used for support during construction.

Almost as impressive is the King's Chamber which measures 10.30 x 5.15 m x 5.80 m high. The form of the roof is unique: above the roof of the chamber itself, composed of nine heavy granite slabs, are five compartments one on top of the other (9) (Fig. 117) separated by stone slabs that act as struts, with a gable roof above the upper-most compartment. Whereas this form of construction could hardly be described, in modern terms, as a conventional solution to the problem of thrust on the roof of the chamber, it shows that the architects appreciated the severity of the problem. The fact that most of the slabs are cracked whereas the King's Chamber itself is intact shows that actually the solution was successful.

For Chefren's pyramid the burial chamber was located in the underlying rock. The chamber is less wide (4.95 m) than that of

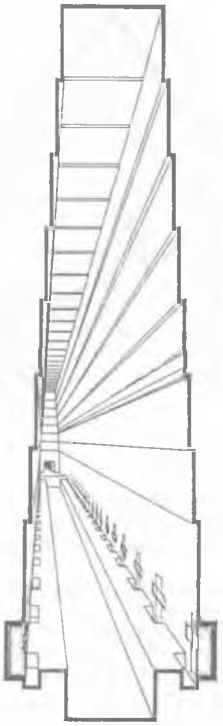


Fig. 118 - Grand gallery in the great Pyramid of Khéops after Capart J. and Werbrouck M - (1930).

Cheops and the roof is pointed, with the slabs laid at the same angle as the side slopes of the pyramid itself, thereby reducing the thrust on the chamber. For the pyramid of Mycerinos, the third in the Giza group, the architects returned to the original solution adopted by Imhotep at Saqqarah, with the burial chamber located well down in the underlying rock.

By the time of the 11th dynasty at Thebes the pyramid had become of secondary importance and the burial chambers were located deep in the underlying rock: in the tomb of Neb-hepet-Re Mentuhotep the descending corridor is more than 150 m long.

However, during the 12th dynasty the Pharaohs Sesostris II and Amenemhet III introduced the technique of building corridors of fired brick, and the burial chambers are again located in the heart of the pyramid. The second pyramid of Amenemhet III, at Hawara, contains an intricate maze of corridors, false doors, huge 20 ton slabs of rock forming trap doors, and false wells filled with rubble in an attempt to hide the true location of the burial chamber from would-be plunderers. The burial chamber itself is very significant from an architectural point of view. The sequence of construction was as follows. Prior to commencement of construction of the superstructure a large rectangular shaft was sunk into the rock and lined with stone (Fig. 119). Into this shaft the burial chamber, composed of a single block of yellow quartzite, weighing 110 tons and shaped like a box without a lid, was lowered. (The block was 6.60 m long, 2.40 m wide, 1.90 m high). The roof of the chamber consisted of three slabs of yellow quartzite lying side by side, each measuring about 1.20 m in thickness. These slabs did not rest directly on the walls of the monolith, but were laid on a course of stone blocks placed on top of the walls in order to heighten the ceiling of the room. Above this there were two relieving chambers, the lower with a flat roof, and the upper with a pointed roof composed of limestone blocks, each weighing 50 tons. Finally, above the pointed roof, an enormous brick arch, 0.9 m thick, was built to support the core of the pyramid.

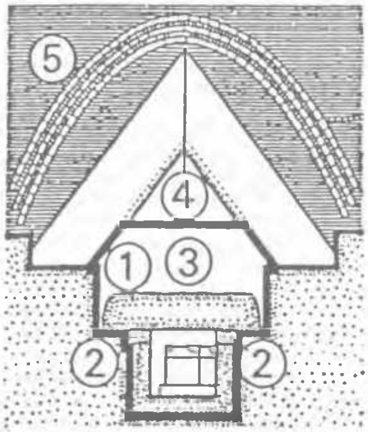


Fig. 119 - The burial chamber of Amenemhet III, after W.M.F. Petrie.

1 - Three slabs of yellow quartzite
2 - Blocks to raise the roof level
3 - Lower relieving chamber
4 - Upper relieving chamber
5 - Brick arch, 90 cm thick

Clearly the purpose of the design was to spread the load around either side of the chamber. It is a remarkable structure and heralds the construction of the curved arch.

As can be seen the Egyptians tried many different solutions for the construction of the burial chambers of the Pharaohs. They found that locating the chamber in the heart of the pyramid could present problems, especially if the strata underlying the pyramid were compressible. Similarly the solution of partially embedding the chamber in the ground was not without difficulties. From the 4th dynasty onwards the chamber was located in the rock beneath the structure, sometimes at considerable depth, although the Pharaohs would surely have preferred a location less distant from the sun, to which they would eventually return. Later the gable roof replaced the corbel vault and finally the relieving arch was introduced, and we have arrived at the remarkable solution provided by Amenemhet III.

2-3-2 - Burial chambers excavated in rock

A highly detailed study of the long-term stability of the tombs in the Valley of the Kings, near Thebes, has been undertaken under the patronage of the Brooklyn Museum. The findings were presented to our Xth International Conference by G. Curtis and J. Rutherford (1981). The survey located a total of 62 tombs, built between 1500 and 1100 B.C., of which 25 were filled with debris and another 12 were otherwise inaccessible.

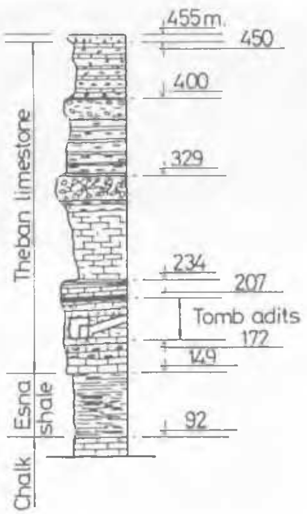


Fig. 120 - Statigraphic section of the Valley of the Kings.

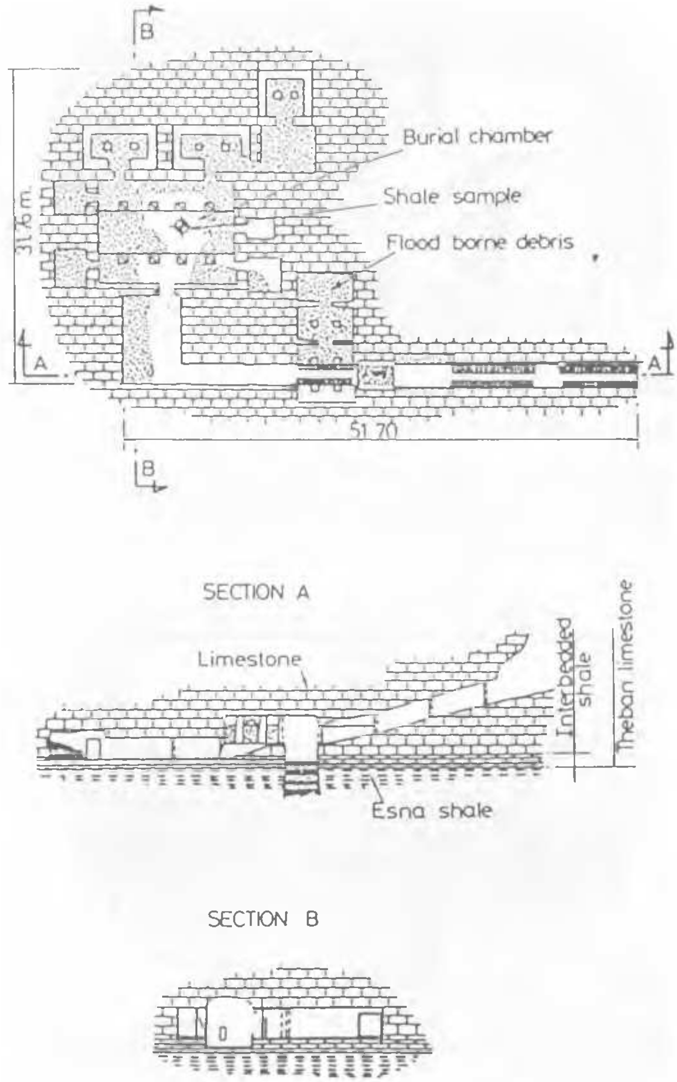


Fig. 121 - Plan and Sections, Tomb of Ramesses II.

The tombs were excavated in a rock cliff face, and extended as far as 175 m horizontally and as deep as 100 m. The rock is a marine limestone overlying an expansive shale (Fig. 120).

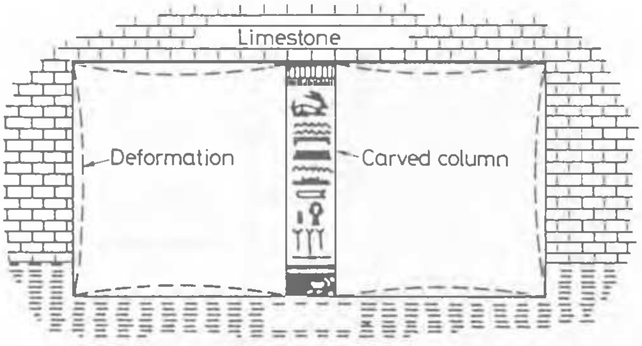
The tomb of Ramesses II (Fig. 121) comprises several rooms measuring about 7 m x 14 m and the burial chamber which measures 14 m x 13 m and includes eight pillars. The roof is flat.

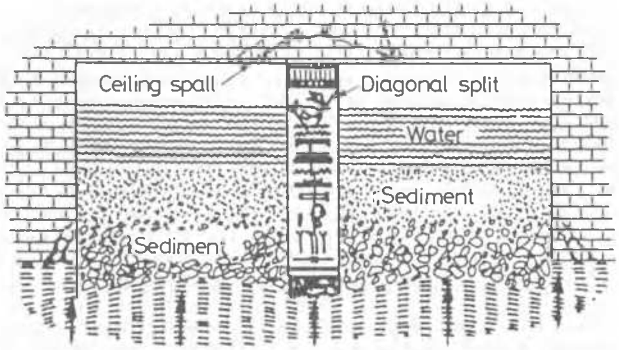
There are a number of reasons for the serious degradation of these tombs, of which the two most important, according to Curtis and Rutherford, are:

1) Flood - caused shale expansion (Fig. 122)

2) Rainfall - caused rock joint widening (Fig. 123)

Thus both causes are related to rainfall. Even though the annual rainfall is usually less than 10 mm in this region it is produced in a few violent downpours, which helps explain how so little rain could cause such serious damage. It goes without saying that for such a depth of rock cover the choice of a rectangular vertical section for the chambers can only exacerbate the situation, by producing stress concentrations at the corners.



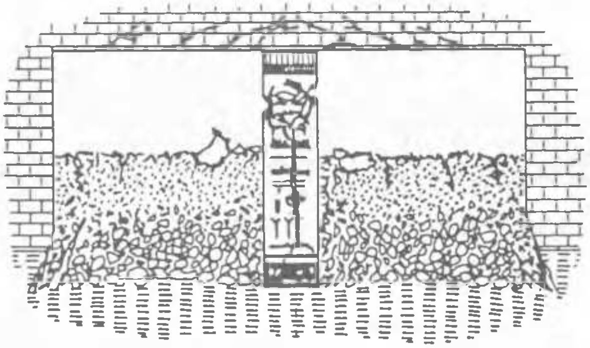


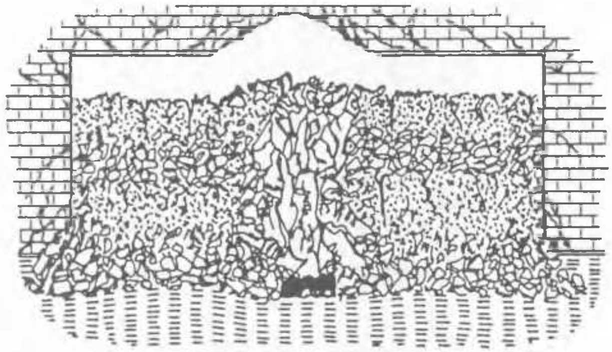
PHASE 1: Initial Excavation

Overburden pressures on rock excavated for tomb chamber exceeded 300 000 kg/m^2 in some cases. Minor deformation and over-break occurred during stress redistribution following excavation.

PHASE 2: Flooding and Swelling

Flood-saturated expanding shales exert enormous upward force on rock pillars and partitions, splitting walls and columns.





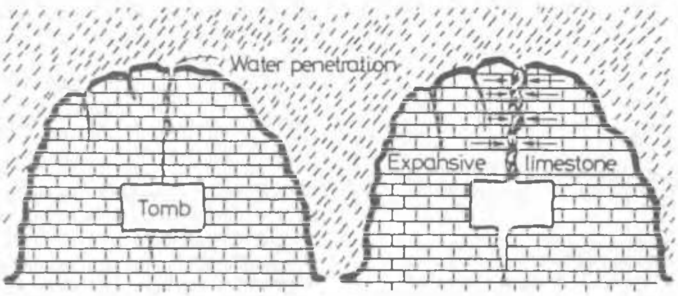
PHASE 3: Desiccation

The drying shale slowly shrinks, leaving portions of broken columns and walls hanging from the roof structure.

PHASE 4: Collapse

After several flooding and drying cycles the ceiling spalls and hanging members drop into the flood debris.

Fig. 122 - Flooding and Expansion Mechanism (G. Curtis and J. Rutherford)



PHASE 1: Rain penetrates joints in expansive limestone

PHASE 2: The limestone expands and the joints gradually fill with rubble, wedging the joints wider with each cycle.

Fig. 123 - Rock Joint Widening Mechanism (G. Curtis and J. Rutherford)

X - EARTHQUAKE RESISTANT DESIGN OF THE GREEKS AND THE CHINESE .

The book of Amos (written around 775 to 750 B.C.), in the Old Testament, opens as follows: "The words of Amos, one of the sheep-farmers of Tekoa, which he received in visions concerning Israel during the reigns of Uzziah (1) king of Judah and Jeroboam son of Jehoash king of Israel, two years before the earthquake. He said:

> The LORD roars from Zion
> and thunders from Jerusalem;
> and shepherds' pastures are scorched
> and the top of Carmel is dried up."

The date of the earthquake is not known but it is also mentioned in Zechariah (around 620 B.C.), Chap. 14 verses 3 to 5:

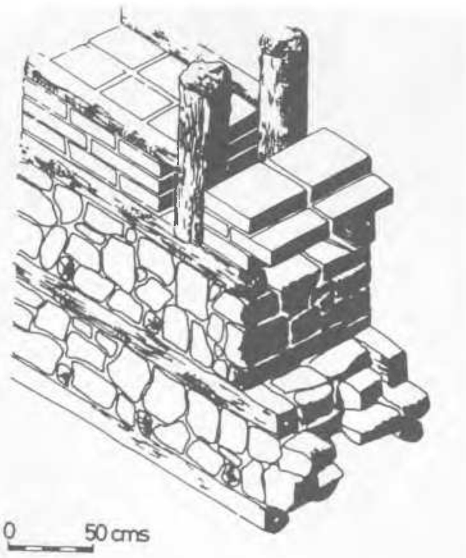
> "The LORD will come out and fight against the peoples, as in the days of his prowess on the field of battle. On that day his feet will stand on the Mount of Olives, which is opposite Jerusalem to the east, and the mountain shall be cleft in two by an immense valley running east and west; half the mountain shall move northwards and half southwards. The valley between the hills shall be blocked, for the new valley between them shall reach as far as Asal. Blocked it shall be as it was blocked by the earth-quake in the time of Uzziah king of Judah, and the LORD my God will appear with all the holy ones."

There was, therefore, a major earthquake in Palestine around the beginning of the 8th century B.C.

1 - Greek practice

Earthquakes are also referred to in the Homeric Hymns of the 8th century B.C. and there are numerous references and descriptions in the Greek literature that followed. These show that the Greeks were both superstitious and rational: superstitious in their belief in Poseidon Petraios, the god of soil and rocks who could provoke earthquakes, and rational in their observation of warning signs such as the abnormal behaviour of animals prior to an event and certain natural phenomena as the diversion of springs. They were also rational in their careful descriptions of the events themselves: one notable example from the writings of Eratosthenes concerns two earthquakes in 373 B.C. that devastated the region around Corinth. Based on their careful observations they were able to devise highly ingenious anti-seismic measures for the protection of their buildings.

(1) Also known as Azariah, he reigned from 779 to 740 B.C.



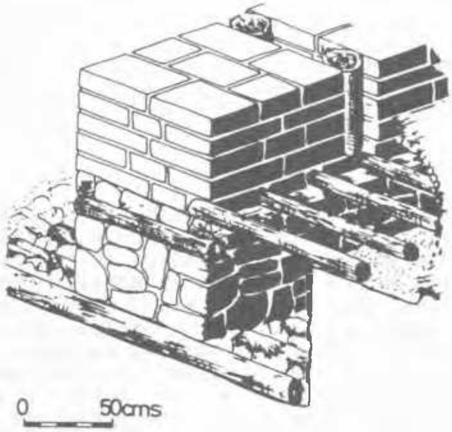


Fig. 124 - The palace at Beycesultan: details of the foundations and of the walls above.

The first such measure was the introduction of wooden beams into the stonework (Fig. 124); at a later date, with the coming of the Copper and Iron Ages, metal cramps linking the dressed-stone blocks together were used, as we have already seen (Fig. 25). These basic elements gave way to ties and complete rings, to stone frames with dovetail joints, with ribs to prevent distortion, to frames set one on top of another and finally to entablatures with plugs superposed and offset for the peristyles. In addition they often made use of random masonry of polygonal blocks (Fig. 125) rather than regular courses of stone.

Fig. 125 - Use of polygonal blocks in Attic architecture of the 6th century B.C. - (underground tank in the Acropolis). From R. Martin, Manuel d'Arch. Grecque Picard Paris 1965 - PI XXXVIII,3.

Furthermore the Greeks did not found their religious structures exclusively on solid rock. One of the Seven Wonders of the World, the Temple of Diana at Ephesus (the Artemesium), built around 560 B.C. and later rebuilt after a fire, was, according to Pliny (XXXVI - 95), "founded on marshy ground in order that it might not feel the effects of earthquakes neither suffer from the cracking of the soil". Nevertheless care was taken to ensure that the bearing capacity of the foundations was sufficient and a layer of compacted cinders was put down and covered by sheeps' fleeces.

The Greeks were aware that the ground transmitted vibrations as witnessed by Vitruvius' account (Book X, Chap. XXII) of the siege of Apollonia:

"When, also, the city of Apollonia was besieged, and the enemy was in hopes, by undermining, to penetrate into the fortress unperceived; the spies communicated this intelligence to the Apollonians, who were dismayed, and, through fear, knew not how to act, because they were not aware at what time, nor in what precise spot, the enemy would make his appearance. Trypho, of Alexandria, who was the architect to the city, made several excavations within the wall, and, digging through, advanced an arrow's flight beyond the walls. In these excavations he suspended brazen vessels. In one of them, near the place where the enemy was forming his mine, the brazen vessels began to ring, from the blows of the mining tools which were working. From this he found the direction in which they were endeavouring to penetrate, and then prepared vessels of boiling water and pitch, human dung, and heated sand, for the purpose of pouring on their heads. In the night he bored a great many holes, through which he suddenly poured the mixture, and destroyed those of the enemy that were engaged in this operation."

2 - Chinese practice

China like Greece is subject to earthquakes so it is not surprising that the Sung Code of 1103 contains measures for the design of seismic-resistant structures. Some of the buildings designed to this code are still standing (Fig. 126). The code imposes the use of white cedar wood, which has a high tensile strength.

Another characteristic of wooden structures is their flexibility due to the large number of joints. The building oscillates in an earthquake but the natural frequency of the building will be much less than the frequency of excitation and so it does not enter into resonance: furthermore the forces of internal friction help to damp out the vibrations. In addition the columns were not fixed in the soil (Fig. 127) and the different arms of the wooden support bracket were isostatic so that horizontal movements would not lead to excessive stresses in the structure.

The outer walls were unloaded i.e. they carried their self-weight only and were what we would today call curtain walls. The roofs were strongly curved in order to reduce the uplift force due to wind, and to promote rapid run-off of rainfall, and very heavy in order to resist the forces acting during a typhoon.

All in all Chinese architecture shows how, by careful thought, they adapted their designs to satisfy certain functional requirements.

The buildings were founded on compacted soil, prepared as we have already seen using techniques illustrated in Fig. 31, and the columns were supported on a wooden base, resting on a stone plinth (Fig. 127). The columns were linked to each other by wooden beams at the base and by slotted lintels at the head; each column was slightly inclined towards the interior (0.8% in a north-south direction and 1% in an east-west direction) thereby improving the stability of the structure as a whole.

Figure 128 shows how the roof was supported by jointed brackets. The roof purlins carry short rafters (no longer than the distance between purlins) thereby providing a flexible structure.

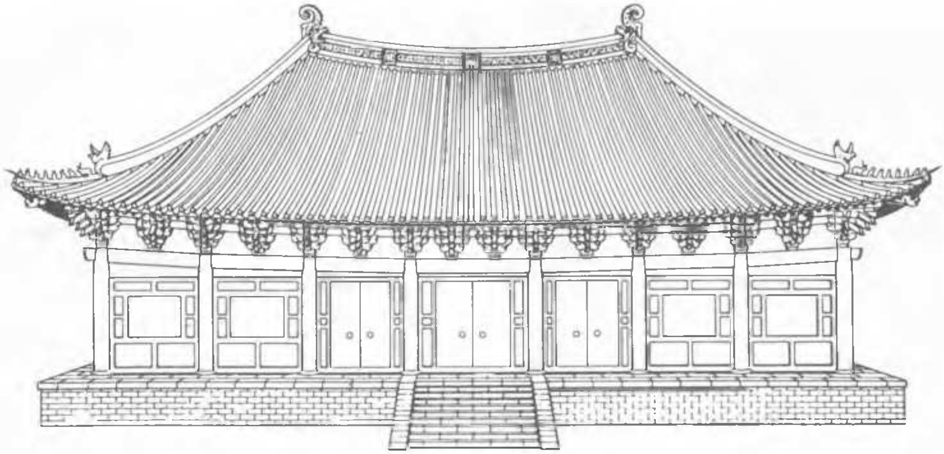


Fig. 126 - Public building dating from the Sung dynasty that is still standing.

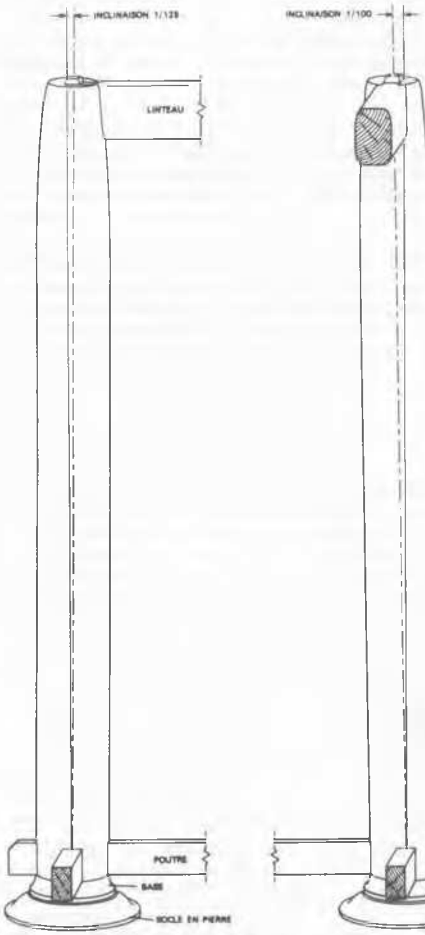


Fig. 127 - Columns resting on stone supports, not encastré , as used by the Chinese .

As a general point, to finish, it may be noted that before 1700 the majority of dams were built of clayey material. Since clay is effective in damping out vibrations none of these dams would have been troubled by earthquakes.

CONCLUSIONS

This series of facts and anecdotes is, then, the first phase of the history of geotechnical engineering.

Man's very existence begins with the soil for it was the shape of his foot and the support provided by the ground that determined his vertical stance and subsequently the development of his brain.

Leonardo da Vinci wrote that "mechanics is the paradise of mathematics". Nevertheless we have seen that for the period up until 300 years ago the mechanics of soils and rocks was practically devoid of any mathematical formulae and that the builders and architects relied on their intuition derived from observations and careful reflection.

The Egyptians directed the thrust in the pyramids downwards to avoid damage to the side slopes; the Greeks, by studying the characteristics of the materials used and the layout of their buildings, refined the proportions and thereby reduced the loads acting on the foundations; the Romans improved the quality of road construction immensely, they invented concrete, they built their structures to

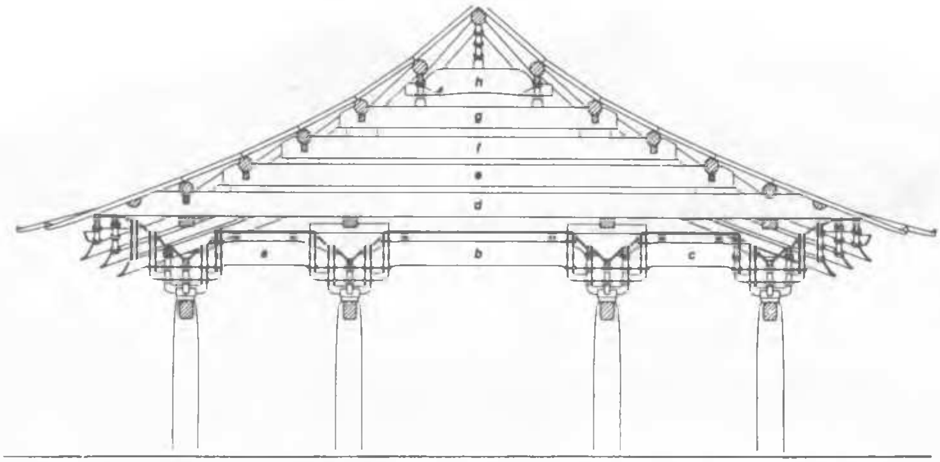


Fig. 128 - Roof supported on columns by means of jointed brackets.

last, and they were the first to draw up codes of practice.

All these civilisations, based on their experience, learnt to spread out the loads to reduce the bearing pressures, and, where the soil was too soft, learnt how to overcome the problem of squeeze. They also discovered that the overturning moment acting on a wall could be reduced by dividing up the soil behind into compartments.

The mortars used in ancient times were made with fat lime which only set very slowly (at the age of a hundred years these mortars were still young). This meant that any structure which did not carry vertical forces only was vulnerable early on in its life.

As pointed out by Russo, whenever some great advance is made the credit tends to be given to that person to whom the advance is directly attributable, while the event is treated as though belonging to a short period in history. In fact in making a discovery the discoverer has made use of all the knowledge relevant to his subject available at that time. In this way one should not disregard the contributions made during the period of history that we have been looking at. Whatever may have become of structures built in the distant past they have left behind clues in the soil in which they were founded.

In this respect we should heed the words of the French philosopher Alain (1958):

> "A man who lies down in the grass writes his form in it, as a dog or a hare does; and since man thinks and tosses around in his thoughts, I may say that man writes his thoughts in his bed of grass. In fact, it is not easy to read this writing; that is why all of the plastic arts are enigmatic. Man himself is an enigma in motion; his questions never stay asked; whereas the mould, the footprint, and by natural extension, the statue itself, like the vaults, the arches, the temples with which man records his own passing, remain immobile and fix a moment of man's life".

From the nathex to the choir in York Minster the furrow traced by this great monument allows us to read the history of the construction of the cathedral from Norman times through to the Gothic period.

We should not be too proud of the behaviour of our structures which apparently have satisfactory foundations. After all would they be able to compare to the Great Pyramid of Cheops after standing for 5 000 years?

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The history of geotechnical engineering is a subject that deserved to be written and we should thank our President V. de Mello for the idea. I am aware that my expose for the period up until 1700 is far from perfect, but I would like to express my thanks to those members of our Technical Committee on Saving Cities and Old Buildings who have provided me with original information, and in particular Prof. Lu Zhao-Jun (China), Dr. V. Nayak (India), Dr. Ing. R. Ortiz (Spain) and Dr. A Jayaputra (Indonesia). I am indebted to M.F. Lizzi (Italy), Dr. M Hamza (Egypt), who sent me the Kitab Al-Ifadah Wa'l-I'tibar, and to Dr. El Kouli, Director of the Service des Antiquités in Egypt, who accompanied me to Meidum and allowed me to follow the excavations, to Dr. R.H.G. Parry, who set me off on the subject of Meidum, to Prof. H.B. Seed for reminding me of sections of the Bible, and finally to Stephen Warren (Cambridge University) for translating my text into English.

ANNEXE I

A NOTE ON ICHNOLOGY

The footprints shown in Fig. 4 were found by Mary Leakey and are of two men who walked across the Laetoli Plain, Tanzania, 3 600 000 years ago. The imprint of the big toe is particularly marked, which corresponds primarily to the digitigrade position of Fig. 3 and shows that during the Pliocene, as long ago as 3 600 000 years ago, one of the ancestors of modern man walked in the same way as we do.

If we take a value of the ratio of the length of the foot to the height of a man, of 0.15:1, the taller of the two men would have been about 1.40 m high and the shorter about 1.20 m.

The shape of a man's footprint for the three different upright postures (Fig. 3) will, of course, depend primarily on the nature of the soil. A large number of footprints of prehistoric man have been found in clay in old cave dwellings. In the plantigrade position the depth and the surface area of the imprints increase with the plasticity of the clay. Where there is a hard layer beneath, the lateral relaxation of the soil increases slightly the distance between the imprint of the toes and that of the metatarsal bar. Similarly any footprint of a creature in motion will be slightly longer than the footprint for the stationary case, regardless of the soil.

Many different factors decide the form of a footprint, including the nature of the soil, its homogeneity over the length of the imprint, and most of all the manner in which the imprint was made, that is the creature's gait, which determines the normal and tangential stresses acting. For quadrupeds the situation is more complicated than for bipeds, since they do not all walk in the same manner. The usual gait is where the two legs diagonally opposed move forward together, while the other two push forward. However, certain animals, including the camel, the elephant, the giraffe, the bear, and some trained horses, move their two legs on the same side together: they are lateral bipeds. Finally, the form of the footprint will, of course, depend on whether the animal is trotting, galloping or jumping.

We can see that ichnology is much more complicated than soil mechanics, where we usually need only consider the static condition, which explains the recent development of the branch of science called experimental ichnology: in this the scientist experiments with bipeds and quadrupeds moving at different speeds and different gaits over a variety of surfaces ranging from hard (where Mercurochrome may be used to give a mark) to very soft. Even so the mark made will vary with the mood of the animal at the time of making the foot-

Fig. 129 - Tracks of a Sauropoda, left in the clayey soil in the River Niger 135 million years ago. (Photograph courtesy of Prof. Ph. Taquet, Directory of the French Institute of Palaeontology).

print. Perhaps the Sauropoda who walked in the River Niger (Fig. 129) 135 million years ago was a bit of a dreamer. What is certain, however, is that the applied bearing pressure beneath the Sauropoda's foot exceeded the bearing capacity of the soil, as witnessed by the heaved material around the perimeter of the footprint.

ANNEXE II

A NOTE ON SOME LEANING MONUMENTS

Italy possesses many of the world's finest ancient monuments and, since many were poorly founded, offers the tourist the view of a number of interesting leaning towers.

The Tower of Pisa is the best known of those towers where the tilt continues to increase. I have also alluded to the Campanile of Burano (Kerisel (1975)); this is a very slender structure, with a height of 53 m and a square base of side 7.50 m. In 1964 an attempt was made to stabilise the structure, at which time the tilt was 5.8%. The tilt has since increased to 6.4%.

Two other leaning towers of particular interest stand at the centre of Bologna (Fig. 130), just 11 m apart. The taller of the two, the Asinelli, is 97 m high with a cross section of only 9 m x 9 m, and leans towards the west by 2.7%. The shorter tower, the Garisenda, leans by 6.7% towards the east. The two towers lean in opposite directions, therefore, which may explain why a wooden corridor, 30 m above ground level, once linked the two together.

The Garisenda, built in 1110, was apparently originally much taller than it is today. It is believed that it was shortened (the word in Italian is mozzata) under the orders of Oleggo di Visconti de Milan (hence his nickname torre mozza), who ruled in Bologna from 1351 to 1360.

The Asinelli is founded on a 5 m-thick masonry base which it is thought is supported on piles (Fig. 131), although this is not known for certain. A number of drillholes undertaken close to the tower, between 1973 and 1975, show that beneath the base the soil is a heterogeneous but firm marly black clay. The percentage core-recovery in the drillholes was high, but the logs show the presence of gypsum, and water losses were recorded during the drilling. Little is known about the foundations of the Garisenda.

For the Asinelli it is possible to deduce, to some extent, how the tilt has developed with time. A fire in 1399 gutted the internal wooden structure of the tower and because the core was overheated it was decided to build an internal facing of brick, laid with horizontal courses at the time. By this means it is possible to estimate the tilt that had occurred before the fire, and that has occurred since. Measurements of the tilt dating back as far as 1774 are available and it appears (Bergonzoni (1980)) that the rate of tilt has been approximately constant since the beginning, with a slight increase in the rate recently. This leads to an estimate of the present rate of tilt of 6.5

Fig. 130 - The two leaning towers of Bologna: The Asinelli (on the right) and the Garisenda - 19th century engraving from Raccolta dei principali monumenti Italiani (Vol 2) Firenze 1845. Ph. Biblioteca Communale Bologna.

seconds per year, which is about the same as that of the Tower of Pisa, although the total tilt of the Asinelli is only about one quarter of that of the Tower of Pisa.

At the present moment the ground surface in Bologna is sinking quite quickly, due to industrial pumping (L. Pieri and F. Russo). In 1977, in some areas, the rate of settlement was a few centimetres per year.

Apparently no remedial measures have yet been decided upon. In fact it is not even known whether the problem is primarily related to the presence of gypsum or to the lowering of the water table.

Another leaning Italian monument is the Ghirlandina tower at Modena, built in several stages. This tower is of square section at the base, but becomes octagonal towards the top, and then pyramidal. Modena is situated in the flood plain to the south of the River Po, where the soils are silts, clays and gravels to as deep as 100 m. Due to pumping (1), the ground surface, between 1962 and

(1) The volume of water pumped per year is some 4 million m^3.

TABLE V

SOME DETAILS OF ITALY'S LEANING TOWERS THAT HAVE NOT YET BEEN STABILISED

	ASINELLI	GARISENDA	GHIRLANDINA	PISA
Date of construction	1100	1100	1099	1170
Height (m)	97	48	88	55
Area of base (m^2)	Square 9.0x9.0=81	Square 7.44x7.44=56	Square 10.64x10.64=113	Circular 140 (ring)
Area of foundations(m^2)	10.4x10.4=108	8.75x8.75=68	12.08x12.08=145	282 (ring)
Mass (tons)	7 300	4 120	9 300	15 700
Load concentration around perimeter (MN/m)	$\frac{7.300\times10}{4\times10.4}$=1.75	$\frac{4.120\times10}{4\times8.75}$=1.17	$\frac{9.300\times10}{4\times12.08}$=1.92	$\frac{15.700\times10}{\pi\times20}$=2.50
Average bearing pressure (kPa)	674	538	637	514
Present tilt rads % degs	2.7 1°27' West	6.7 3°50' East	2.6 1°29' South-west	9.3 5°20'29" South
Rate of increase of tilt (secs per year)	6.5	?	?	7
Soil conditions	Firm heterogeneous clays with lenses of gypsum in the process of being dissolved.		Silts, clays & gravels.	Silts, clays & sand.
Tilt since beginning of construction.	No (without being certain)	Yes	Yes	Yes

1981, settled by an average of 4 cm per year: in Modena the settlements are not uniform and this tower now tilts by 2.6%.

Some relevant information regarding these four towers is summarised in Table V.

Despite its great interest I have deliberately left out of the main text the tower at Nevyansk (in Russia) as construction of this monument did not begin until 1700. The tower is located next to a filled-in river. It is 54 m high and leans by 3.3% towards the old river. The rate of tilt is no longer increasing but the structure continues to settle (Chernyshov et al. 1981).

Details of the German towers listed in Tables III and IV are given below.

St Catherine's church in Hamburg is located close to the port. It rests on a wooden base which, it is supposed, is supported on wooden piles that penetrate through 5 m of peat to found in the sand layer beneath. The ground surface of Hamburg is settling at the rate of about 2.5 mm per year relative to the sea,

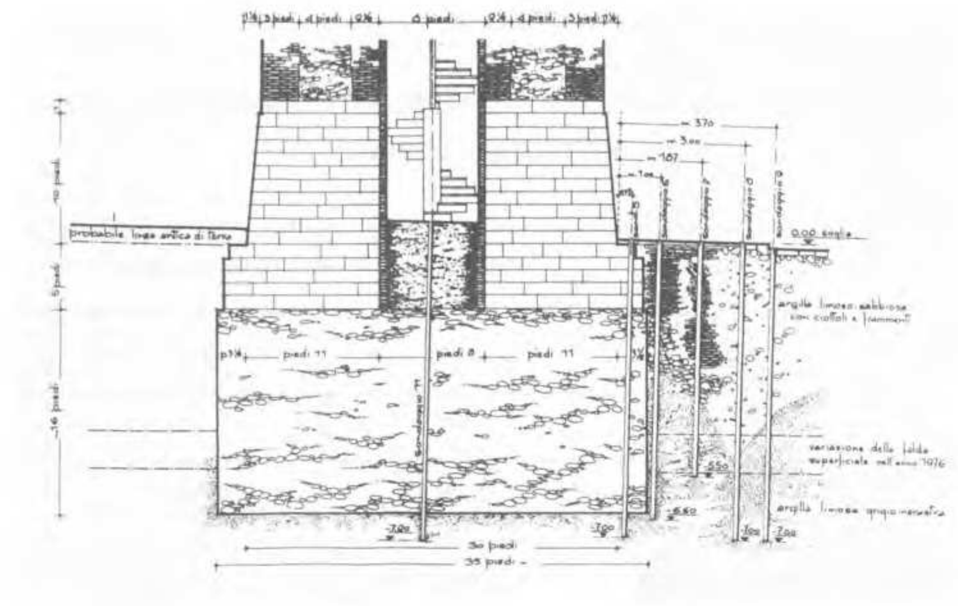

Fig. 131 - Supposed foundations of the Asinelli (vertical section) after F. Bergonzoni.

which would mean a total of 1.25 m over the 500 years since the church was completed. In addition the fill added around the church will have led to negative skin-friction forces on the piles. Furthermore the church was heavily bombed.

The tower weighs 18 000 tons and the dimensions of its base are 14 m x 15 m. It was underpinned in 1968 (Pieper (1982)), before which it was settling at a rate of 4.2 mm per year, while tilt was increasing by 0.05% per year (108 secs.). After the remedial works the settlement had reduced to an average of 0.5 mm per year.

At Lubeck the soil comprises layers of silts, clays and sands, and a condition of flow exists in the groundwater.

The cathedral towers weigh slightly more than the towers of the Marienkirche, but the foundations are slightly larger, so the bearing pressures for the two structures are approximately the same; it is not surprising, therefore, that the towers for both monuments lean by approximately the same amount (3.8%) (Table IV).

For the cathedral the foundations are 14 m wide and the differential settlement is 45 cm, which over 700 years amounts to an average value of 0.6 mm per year. Towards 1930 the tilt appeared to be stabilising but due to bombing during World War II it then increased to about 40 secs per year. It was stabilised by installing inclined piles beneath the west wall, in an operation that turned out to be far from simple (Smoltczyk (1981)).

The Marienkirche was seriously weakened by bombing during the Second World War. It was repaired by strengthening the structure internally, rather than underpinning.

As regards the minaret of Al-Habda Mossoul, which leans by 9%, relatively little is known. The superstructure is certainly in a very poor state and this may be the main cause of the tilt. There is no reliable information available on the foundations.

ANNEXE III

THE STRENGTHENING WALLS IN THE EGYPTIAN PYRAMID AND THEIR STABILITY

Recap on arching theory.

Consider a granular material retained by two rough walls a distance b apart. We know from experience that with depth the stresses in the soil tend towards constant values (Fig. 132). The material behaves as if parabolic arches form, ABC A'B'C', the weight of the soil being carried by friction on the side walls. Thus the weight of an arch of thickness z, $\int \gamma\ z\ \ dx = \ \gamma\ zb$, is carried by shear stresses on either side

$$\tau_\infty = \frac{1}{2}\gamma b$$

while the corresponding normal stresses are

$$\sigma_\infty = \frac{1}{2}\ \gamma b \text{ cotan } \emptyset$$

At finite depths the corresponding stresses τ and σ increase from zero following an exponetial law, thus (Caquot et Kerisel (1966)):

$$\frac{\sigma}{\sigma_\infty} = 1- \exp\ (-\frac{h}{b_1})$$

where $b_1 = b . f(\emptyset)$ and for $\emptyset = 30°$, $f(\emptyset) \simeq 2.$ This yields the following results:

$\frac{h}{2b}$	0	0.5	1	2	3	4	5
$\frac{\sigma}{\sigma_\infty}$	0	0.39	0.63	0.86	0.95	0.98	0.99

Inclined walls

Arching theory may be modified quite easily for the case of walls that are inclined. Thus Imhotep's design was for an inclination of 72° to the horizontal: with reference to Fig. 133, the weight of the retained material may be resolved into an inwardly acting force γzb sin 18°, and an inclined force γ zb cos 18°. We can then make the simplifying assumption that in the expressions derived above it is sufficient to replace the term γ zb by γzb cos 18°. In fact the inwardly acting force γzb sin 18° will increase the tangential stresses acting on the face DE. Nevertheless the coefficient of friction on this relatively smooth face will be less than that for A'C'. The two effects tend to cancel each other out, so our simplifying assumption is reasonable.

The stability of the walls of Meidum pyramid

We will analyse the stability of one of the exposed walls at Meidum pyramid, between two steps (Fig. 134), since the walls (5.2 m thick) are thicker than those at Saqqarah (2.6 m thick) and therefore more critical.

The average side slopes of the pyramids at Meidum (E_2) and Saqqarah are at 52° to the horizontal. This is the inclination of a line such as AB (Fig. 134) joining two identical points on different tiers. Since the steps are 5.20 m wide and the exposed face is inclined at 72°, the length of the

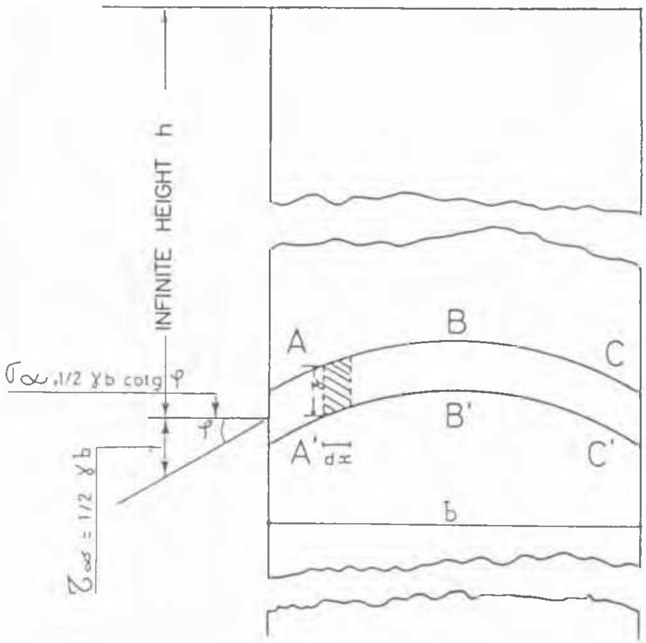

Fig. 132 - Arching stresses for a granular material retained between two vertical walls.

Fig. 133 - Arching theory for sloping walls.

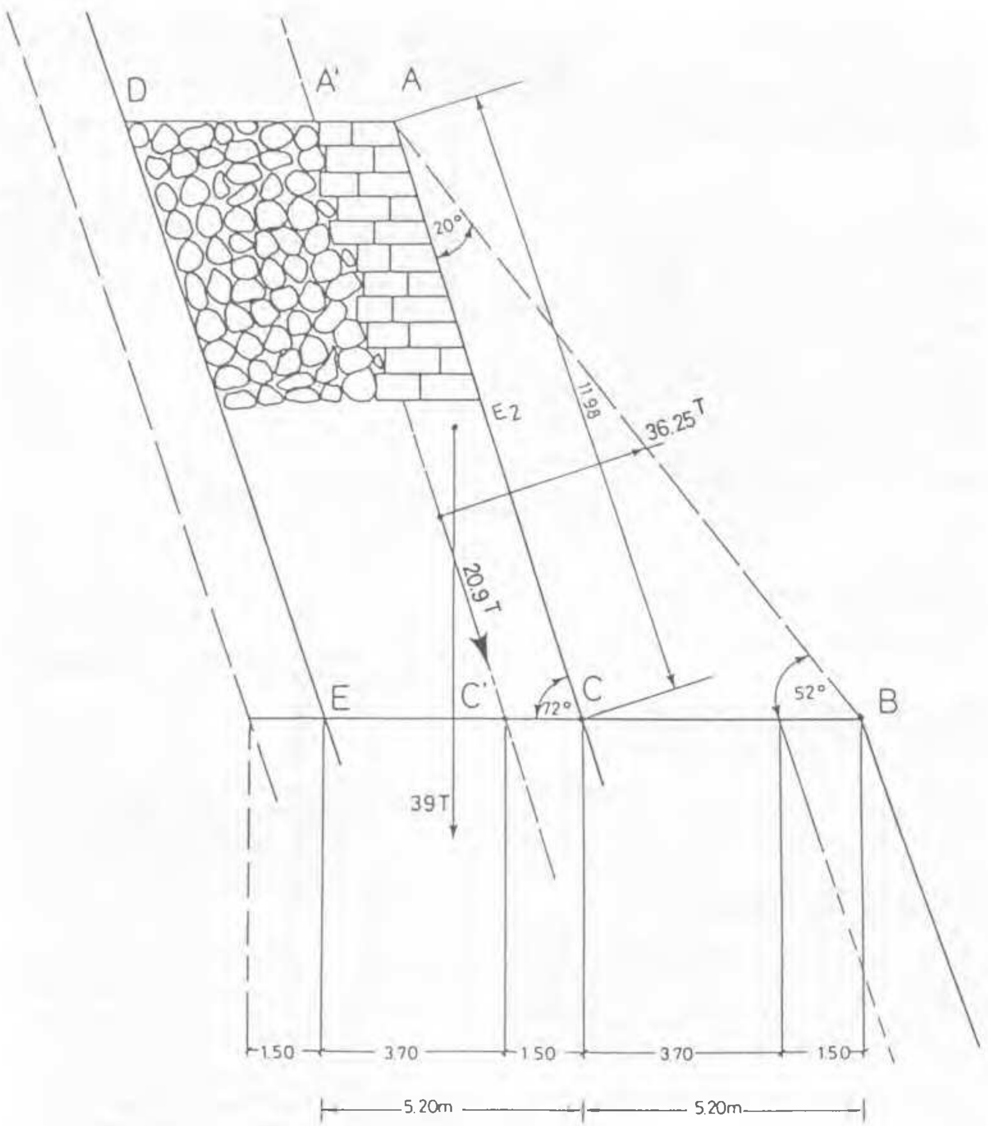

Fig. 134 - Meidum - Stability of a wall between two steps.

exposed face is calculated as follows.

$$AC = 5.20 \frac{\sin 52°}{\sin 72-52°} = 11.98 \text{ m}$$

This gives the length of wall on which the destabilising earth pressures act. To calculate these earth pressures it remains to select values of γ, b and $\emptyset$. The

density of the limestone is only 2.30 t/m^2, and if we assume that voids take up 13% of the space this gives us a value of

$\gamma \approx 2.0 t/m^3$. The thickness of the retained material is the wall thickness (5.20 m) less the combined thickness of the facing blocks and the "backing stones", which are blocks of rock which are less well shaped but were nevertheless laid in courses. If we take a figure for this latter thickness of 1.50 m, we obtain a value of b=3.70 m, although it must be remembered that this figure is rather arbitrary. A value of $\emptyset$=30° will be taken for the angle of friction acting between the retained material and the backing stones, along A'C'.

Substituting into equation (1), we obtain:

$$\sigma_\infty = 1/2 \times 2 \times \cos 18° \times 3.70 \times \text{cotan } 30°$$
$$= 6.09 \text{ tons/m}$$

and at different levels along A'C':

Distance from A'(m)	0	1.85	3.70	7.40	11.10	11.98
σ (t/m)	0	1.34	2.37	3.83	4.72	4.89

The total outward acting force is found to be 36.25 tons (per m of wall) and the correspond frictional force on the back of the backing stones is 36.25 tan 30° = 20.9 tons. The weight of the blocks is 2.3 x 1.5 x 12 x cos 18° = 39.4 tons. These three forces are shown on Fig. 134.

By taking moments about C we find:

overturning moment = 164.4 ton m
restoring moment
i) weight of wall = 39.4x2.5=98.4 ton m
ii) shear force on A'C'
= 20.9x1.4=29.6 ton m

So that the ratio

$$\frac{\text{overturning moment}}{\text{restoring moment}} = \frac{164.4}{98.4+29.6} > 1$$

We see therefore, that adopting a thickness of 5.20 m for the walls of Meidum was a risky venture. As for the pyramid at Saqqarah, the same calculation for a wall thickness of 2.60 m shows an adequate factor of safety, which explains why the pyramid is still standing, essentially undamaged, even though the facing blocks of Tura limestone have been removed.

Besides overturning, however, we also need to check for sliding along the plane CC'. The calculation of the required coefficient of friction is given below:

$$\frac{36.25 \cos 18° + 20.9 \sin 18°}{-36.25 \sin 18° + 20.9 \cos 18° + 39.4} = 0.85$$

so that an angle of internal friction of 30° (tan 30°=0.577) is insufficient. Of course the angle of friction chosen, 30°, is rather arbitrary and perhaps a bit pessimistic. In addition the thickness of the facing blocks is not known, so it cannot be pretended that these calculations are highly accurate. They do however give an idea of the relative magnitudes of the forces acting. The greatest unknown is the effect of the degree of order introduced in shaping and placing the filling material, since the blocks were not placed completely randomly. In arching theory it is assumed that there is no preferential layering of this material so that the angle of internal friction ϕ may be related to the angle of friction between two flat surfaces ψ, which is approximately equal to the residual angle of friction, using $\tan \phi = \frac{\pi}{2} \tan \psi$ (Caquot 1934).

A careful examination of the blocks at Saqqarah shows that they tend to be arranged preferentially, in horizontal layers, so that the destabilising forces are thereby reduced. At Meidum the blocks are less well shaped, but there is some evidence for preferential horizontal layering (see Fig. 59). This would help explain why the exposed walls are stable over a height of some 30 m. Thus without going so far as using dressed stones throughout their pyramids, the Pharaohs were able to improve the stability of the walls by using blocks that were roughly shaped and that were laid in a manner that produced a certain degree of order.

ANNEXE IV

THE STABILITY OF THE RETAINING WALLS BUILT BY VAUBAN AT YPRES

The retaining walls of the fortification at Ypres are particularly interesting because we know Vauban's reasoning on the causes of the failures and his arguments for the remedial measures undertaken.

References to the site are made by Bélidor (1810) and by General Poncelet (1840) who commented on the drawings of Hue de Caligny (1), who collaborated with Vauban on the project. As we know today, retaining walls founded on clay always present difficulties, and up until 1684 when Vauban published his tables for the construction of retaining walls he had come across clay at only a few sites, which explains why there had been no failures at any of the 150 forts that he had built.

Details of the original walls at Ypres, which failed around 1678, are found in a document which dates from "around 1687", belonging to the "Service Historique de l'Inspection du Génie".

(1) see Augoyat (1839)

The document states that the movement "blew the soil up in front of the walls". The highest wall was 40 pieds (feet) (2) high and was founded at a depth of 8 pieds on pillars 10 pieds wide "as much wall as void", i.e. covering half the available passive area. It is stated in the document that this would mean that only half the available soil resistance was used, but this is a bit conservative as it ignores the adhesion on the sides of the pillars.

Vauban made the new walls continuous below ground level and adopted a ratio of depth of embedment to retained height of slightly less than 1 to 2 : for the wall shown in Fig. 135 the ratio is 14 to 35, while elsewhere ratios of 9 to 19 and 6.5 to 15 are found. The trenches were excavated using pickaxes, and the sides were timbered, which, according to Poncelet (1840), was to prevent the soil from softening, thereby preserving the strength of the soil and the passive resistance.

The second cause of failure, besides insufficient embedded area, was, according to the writer of the document, that the spacing of the counterforts of 20 pieds was too great. Vauban reduced this figure to 15 pieds.

It was believed that a third cause of failure was that the backfilling was placed before the mortar in the wall had aged

(2) 1 pied = .325 m

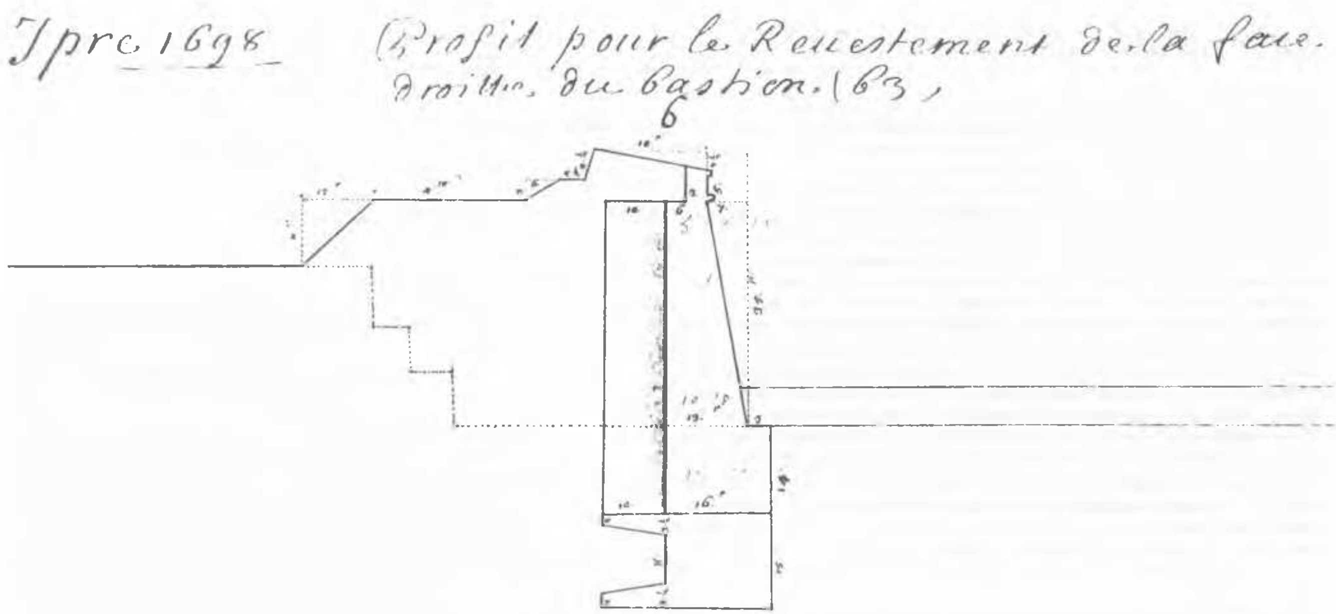

Fig. 135 - Retaining wall at Ypres built by Vauban

sufficiently. The same reason was given for the failure of the wall of the Minimes lock on the Canal du Midi (see section VIII), which dates from the same period.

As an additional safety measure, Vauban insisted that the soil behind be benched over the full height in order to avoid "the effect of the wedge". This benching, in the form of a staircase, is shown as a dotted line in Figs. 88 and 135. We see that Vauban appreciated that failure involved a sliding wedge of soil.

As we do not know the appropriate soil parameters, nor the conditions of drainage, a detailed stability calculation is not possible, either for the old walls or the new ones. However if we assume a value of the undrained shear strength of the clay of 50 kPa we can calculate by how much the resisting force was increased.

By adopting a continuous profile below ground level, rather than a combination of arches and pillars, the effectiveness of the wall would be increased in the ratio of about 15 to 20. As the depth was increased from 8 pieds to 14 pieds, the overall increase was

$$\frac{20}{15} \times \frac{14}{8} = 2.33$$

The passive resistance per m would be

$$14 \times 0.325 \times 2 \times 50 = 455 \text{ kN}$$

while the resistance to sliding along the base of each wall would be

$16 \times 0.325 \times 50 = 260$ kN (this ignores friction on the counterforts, as they became detached from the walls).

Thus the total resisting force per m of the original walls was

$$\frac{455}{2.33} + 260 = 455 \text{ kN}$$

while for the new walls it was

$$455 + 260 = 715 \text{ kN}$$

which represents an increase of 57%.

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