CHAPTER 5

Subsidence in Coastal Lowlands Due to Groundwatcr Withdrawl: The Geological Approach

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ABSTRACT: The vulnerable situation of coastal lowlands with respect to flooding is aggravated by land subsidence due to groundwater withdrawal. Because of the growing demands of the ever increasing population, industry and tourism, excessive and uncontrolled pumping is the order of the day in most of the great coastal cities. Therefore, well-balanced groundwater management has become imperative for the survival of these sinking cities.

Groundwater management implies geotechnical and hydrogeological research. The geological data, however, still form the basic framework, but geological data can only be useful if the three-dimensional spatial extension of relevant units is delineated. The elaboration of the geometry based on the knowledge of processes responsible for the deposition of the sediments and the formation of their facies is analysed. The analysis is illustrated with the case study of land subsidence in Shanghai (China).

INTRODUCTION

Coastal lowlands belong to one of the most vulnerable regions to coastal hazards. In particular, those along major rivers forming vast flat plains are prone to all kinds of coastal changes, as they are seldom situated at a level higher than high water level. Besides storms or hurricanes which are catastrophic although occasional, these areas are continuously threatened with the risks of coastal erosion, salt-water intrusion, disturbance of the natural drainage and, above all, flooding.

The flooding, however, most of the time is not produced by the sea, but originates from the land itself. Due to the very low lying situation of the plains, exhibiting no significant relief, they all experience a certain deficiency in drainage. Most frequently it is the heavy rainfall over the mainland which cannot sufficiently be drained to the sea that causes the floods (Figure 1). These floods, in a way inherent in the development of coastal lowlands, would not be hazardous if so many lives weren't involved with the consequences.

Indeed, since ancient times, coastal plains belong to the most preferred areas for human settlement. Soil fertility, availability of fresh water from the rivers, accessibility because of the flat relief, and sea and waterways as first-rate trade routes, make coastal plains valuable agricultural and economic resources. Consequently, these plains belong to the most densely populated areas in the world. At river mouths, many cities developed into enormous seaports and industrial centres and are present-day world metropolises (Table 1).

However, these giant cities are presently aggravating this vulnerable situation to a great extent. Because of the dense population and the industry, and in the past few decades because of tourism, the demand for fresh water is very high in the metropolitan areas. River water is commonly polluted and the use of it requires expensive treatment and reservoirs; hence, groundwater is pumped from the aquifers in the subsurface. The catastrophic consequence of groundwater withdrawal in the coastal plain, however, causes nearly instantaneous local land subsidence due to sediment compaction.

Indeed, land subsidence has become an alarming phenomenon of the giant cities in the modern coastal plains, transforming them into the sinking cities of the world. The city of Venice (Italy) is well known, but is a small case with mainly historical background. More serious are the metropolises with a concentration of millions of people living at or even below mean sea level (Figure 2). Examples of recorded land subsidence are listed in Table 2. But many other big cities, in particular in the Third World, have no record of their subsidence which, moreover, is far from being under control (Jakarta, Hanoi, Haiphong, Rangoon, Manila) (Figure 3).

Literature abounds with studies on land subsidence. Textbooks, special issues and proceedings from conferences describe at length many aspects of the subject (*e.g.*, POLAND, 1984; HOLZER, 1984; JOHNSON *et al.*, 1984; JOHNSON, 1991). The geotechnical engineering of soft sediment compaction is very well documented too (*e.g.*, RIEKE and CHILINGARIAN, 1974; BRAND and BRENNER, 1981). So why another extensive paper on land subsidence?

The control of land subsidence due to groundwater withdrawal requires proper groundwater management. Such management can be successful by using an adequate mathematical model. For the elaboration of a model, however, accurate quantitative information of the geotechnical, hydrogeological and geological conditions are badly needed.

Investigations on land subsidence are always approached from an engineering side. The main emphasis is put on the

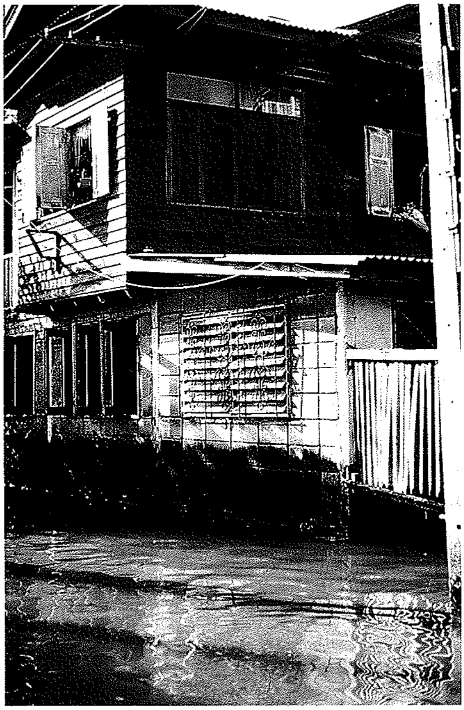

Figure 1. One of the numerous houses in Bangkok Metropolis which regularly suffers from floods when the Chao Phraya and the local drainage system (klongs) cannot sufficiently discharge the water from rainstorms to the sea. The picture was taken at the beginning of the rainy season, and from the level of the algae on the wall, the worst is still to be expected.

geotechnical and hydrological conditions. Consequently, geological data are never considered properly. Very often, the geological setting is simply recalled as a kind of introductory data, most of the time on a postage-stamp-like scale (Figure 4).

However, there is much more information to show and to know than is usually depicted on the geological maps where the lowlands are unicoloured, with a legend only mentioning "Quaternary" or "Recent Deposits". Even the generalized cross-sections *à la pancake geology* (HAGEMAN, 1984), where broad stratigraphical units are correlated assuming that the units remain regular and uniform between the data points, are imprecise data and consequently disappointing all the time. They only lead to misinterpretation and false conclusions about the geological setting in the first place and about all other relevant characteristics conditioning compaction in the second place (Figure 5).

The deposits, in particular the changing spatial distribution of their facies, lateral and vertical, initially account for the geotechnical and hydrogeological properties. And it is especially these changes in the characteristics of the deposits and their spatial distribution that must be depicted in detail in order to describe the properties conditioning compaction.

The objective of this paper is to analyse how to deal with the geological data in order to make them usable for land subsidence research. The analysis is illustrated with some examples from the case study of Shanghai (China) (Figure 6) which experienced significant land subsidence due to uncontrolled groundwater withdrawal (Figure 2). In order to control the subsidence, a flow-compaction model (3D

Table 1. *List of major metropolises located in coastal plains, ranked by population size (population in million, DOGAN, 1988).*

Tokyo (Japan):	17,2
Shanghai (China)—Changjiang River:	12,0
Buenos Aires (Argentina)—Parana River:	11,0
Calcutta (India)—Ganges-Brahmaputra:	11,0
London (England)—Thames:	9,8
Cairo (Egypt)—Nile:	8,5
Jakarta (Indonesia):	8,0
Tianjin (China):	7,8
Bangkok (Thailand)—Chao Phraya River:	5,5
St. Petersburg (Russia)—Wolchow River:	5,1
Ho Chi Minh City (Vietnam)—Mekong River:	3,4
Rangoon (Myanmar)—Irrawaddy:	2,4

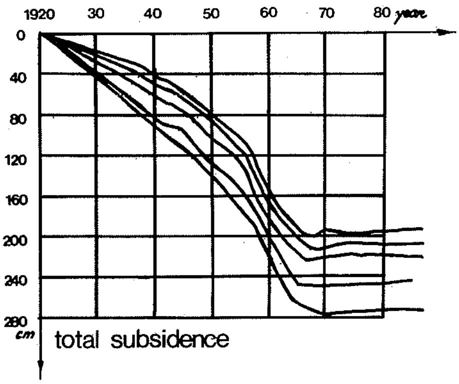

Figure 2. Example of significant land subsidence in Shanghai, China's biggest city, where the total cumulative subsidence is measured at different locations in the central area of the city. Subsidence has occurred since 1921, coinciding with China's period of industrial development. Between 1956 and 1959, subsidence at an annual rate of 98 mm was recorded, and in 1965, it reached a maximum of nearly 3 m. From this data, it was decided to recharge the main aquifer during winters, resulting in a residual consolidation of about 2 to 3 mm a year (after SU, 1984; SHI and BAO, 1984).

Table 2. *Examples of major metropolises and areas with recorded subsidence.*

Po Delta (Italy):	3.2 m	Houston (USA):	2.7 m
Tokyo (Japan):	4.6 m	SW Taiwan:	2.4 m
Shanghai (China):	2.7 m	Taipei (Taiwan):	1.9 m
Tianjin (China):	2.5 m	Ravenna (Italy):	1.2 m
Bangkok (Thailand):	1.6 m	London (England):	0.35 m

Figure 3. A suburb of Metro Manila where natural and man-induced subsidence leads to a deficiency of drainage resulting in severe flooding of the region.

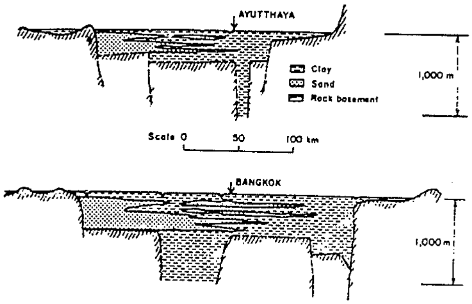

Figure 4. Typical example of a schematic simplified cross-section used in subsidence investigations. This cross-section is mentioned to delineate the geological setting of the Lower Central Plains of Thailand (from NUTALAVA and RAU, 1981).

flow and 1D consolidation) was designed. Therefore, intensive investigations of the geology, hydrogeology and engineering geology were carried out simultaneously, providing the basic elements for the model (BAETEMAN, 1989; BAETEMAN and SCHROEDER, 1990; DASSARGUES and LI, 1991; MONJOIE, 1992).

METHODS

FRIEDMAN and SANDERS (1978) demonstrated very well the complex environment of river mouths and coastal plains when writing: "The mouths of large rivers are *battlegrounds* on which many geologic processes are actively engaged. Some of these processes augment one another; others cancel out. Whatever their combinations, the outcome is to create a series of coastal configurations and to deposit various bodies of sediments".

The various bodies of sediments, however, do have at least one particular feature in common: they are deposited near or below sea level. Hence, the sediments possess a high water saturation or moisture content, and they are unconsolidated and compactible or compressible.

Such unconsolidated sediments compact in response to pressures from load of overlying material, or from structural deformation, or in response to fluid withdrawal. The nearly instantaneous result of the compaction is land subsidence, the lowering of the land surface by mass movement, or the sinking of the earth's surface owing to adjustments in subterranean material (RIEKE and CHILINGARIAN, 1974).

In the case of land subsidence from compaction, the interaction between the geological characteristics on the one hand and the hydrological and geotechnical properties on the other hand must be considered. Such an interaction can be expressed by using the facies of deposits.

Facies is used in the sense of a distinctive rock with specified characteristics that forms under certain conditions of sedimentation, reflecting a particular process in a particular sedimentary environment (READING, 1986; WALKER, 1986). Indeed, certain conditions of sedimentation by a particular process (or interaction between various processes) in a particular depositional environment produce a sediment body that bears well-defined hydrogeological and geotechnical properties, although conditions may change later on.

For the research of the characteristics of the deposits conditioning compaction, it is imperative to emphasize the three-dimensional facies geometry because every particular facies bears its particular geotechnical and hydrogeological properties. Therefore, the spatial distribution of every facies, lateral as well as vertical, must be delimited in detail for the entire area under consideration.

Sedimentological and stratigraphical research must not be limited to the elaboration of a composite stratigraphical column or section which is only subdividing the strata and labeling them with formal names. Such exercises are of no use for determining areas sensitive to compaction, because they only give a unidimensional data point. The restriction of the data to surface information is misleading just as well. Moreover, many hydrogeological and geotechnical unit boundaries differ from boundaries of litho- or chronostratigraphic units (ZAPECZA, 1992).

The hydrological and geotechnical properties are directly related to the facies of the deposits that form the body of the coastal plain. Therefore, knowledge of the depositional and postdepositional history of the deposits in a paleogeographical perspective is essential to the determination of the characteristics conditioning compaction. Furthermore, the elaboration of the geometry can only be based on that knowledge.

DEPOSITIONAL HISTORY AND PROCESSES IN COASTAL LOWLAND ENVIRONMENTS

Coastal Plains

Major rivers entering the sea form a delta or an estuary. The river mouth, however, should not be considered as a separate entity. Neither is the river mouth to be looked upon only as a place where fresh and salt water meet. Together with its surrounding lowlands, the lower reach of the river and its mouth it forms one of the most magnificent and dynamic features in the coastal scenery.

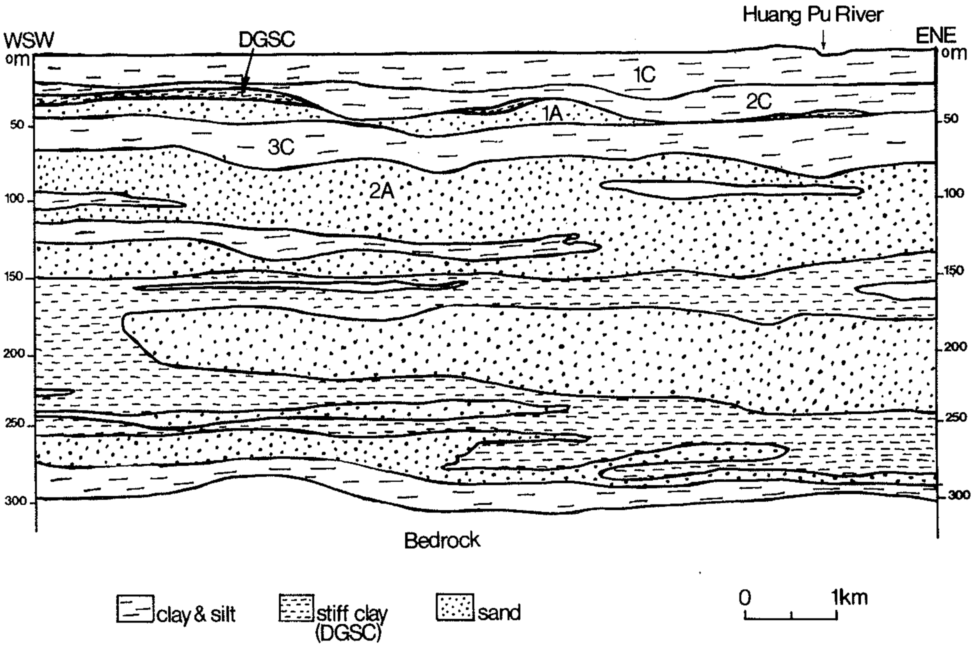

Figure 5. Example of generalized cross-section from the Shanghai urban area. This cross-section, representing the entire Quaternary sequence, is used to form the basic geologic data for the subsidence investigation. The deposits are subdivided into aquifers (A) and compressible layers (C). As compaction mainly occurs in the upper 70 m, only the Pleistocene Aquifers 1A and 2A and the 3C compressible unit and the Holocene 1C and 2C are considered. The Pleistocene/Holocene boundary is formed by an impermeable and consolidated clay unit (DGSC) that was assumed to have a regular extension and hence to seal off the aquifers from the compressible Holocene clay layers so that leakage and dewatering could not happen. However, from such a cross-section, it is impossible to consider the variations in the latero-vertical succession and to deduce accurate quantitative data.

This feature represents complex depositional systems composed of thick sediment accumulations of greatly differing characteristics and environments. It is recognized by the vast low lying flat landscape and called a delta plain or coastal plain.

Several different appellations are used to name these regions: delta, deltaic plain, delta plain, deltaic wetlands, coastal plain. However, in 1973, REINECK and SINGH proposed a comprehensive definition when they described three specific fluvial associations covering the reach of the river deposits from the source to the mouth (Figure 7). Initially, a fourth association was distinguished, *i.e.*, delta-association, but combining delta and coastal association was preferred, because the deltaic deposits nearly always evolve to a coastal plain. The coastal plain association occupies large areas in the lower reaches of rivers and produces thick deposits of fluvial and coastal sediments.

BELKNAP and KRAFT (1977) and KRAFT and CHRZASTOWSKI (1985) describe a coastal plain as a subaerial extension of the continental shelf (seaward margin of the continents) and in reality the coastal plains are an emergent part of the continental shelves. The coastal plains and continental shelves are in fact a single geologic province, and it is, to recall the words of KRAFT and CHRZASTOWSKI (1985), "a happenstance of geologic factors such as sea level, sedimentation, and or tectonics, as to whether or not any part of the coastal plain–continental shelf is emergent or submergent".

Coastal plains are most widely developed in areas bounded landward by extensive folded highlands, or in areas where the through-flowing streams possess very large drainage basins, or in areas with slight to pronounced downward tectonic movement seaward. The course of the major through-flowing rivers and drainage basins is guided generally by adjacent regional structural control. These, in effect, dictate the general areas of emergence of the drainage system at the continental margin and, consequently, the location of the widest coastal plain and the thickest accumulation of sediments in its subsurface (COLQUHOUN, 1968; AUDLEY-CHARLES *et al.*, 1977).

Major rivers like the Indus, Brahmaputra-Ganges, Missippippi, Huang Ho and Changjiang drain large areas and reach the sea after a long passage through alluvial plains. Hence, their sediment load in their lower reaches and at the mouth where they make extensive coastal plains is fine grained. It consists predominantly of silt and clay with

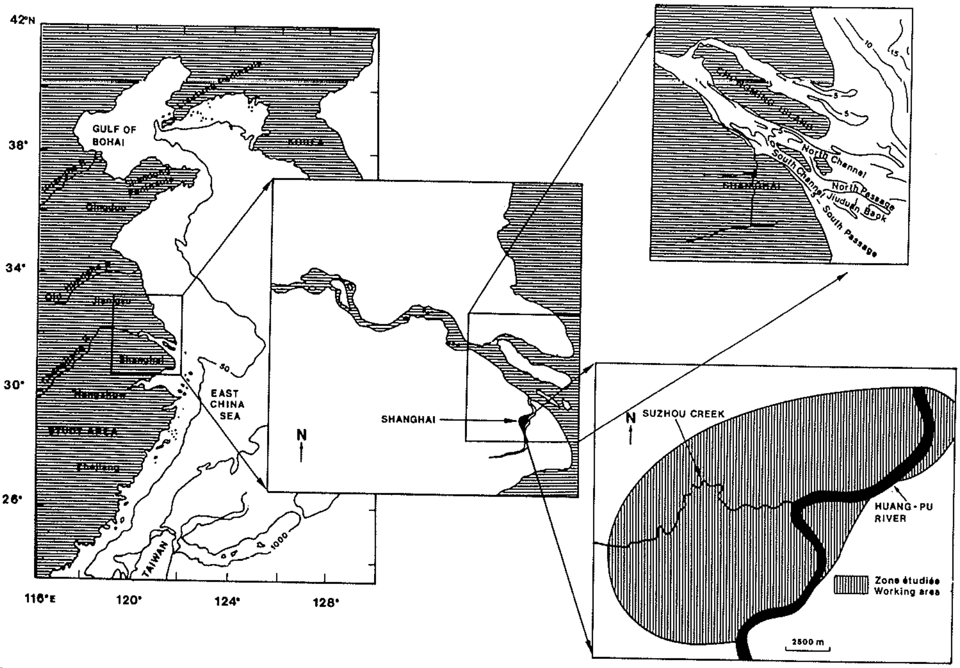

Figure 6. Shanghai is located in a vast low lying coastal plain characterized by the lower reach of the Changjiang (Yangtze) River, a mesotidal estuary. The city is crossed by the tidally influenced Huang Pu River.

minor proportions of sand, the latter mainly restricted to the channels. Gravel is often absent or transported only in very small quantities (EINSELE, 1992). In humid climates, swamps and peat growth may develop.

The sediment discharged by the river sinks where appropriate space is available for it. Such an appropriate space is offered by a tectonic basin where a large body of sediment can be accommodated and preserved for long geological time periods.

Today's modern major rivers form active depositional basins which occur in a wide variety of tectonic settings; however, all are characterized to a certain extent by subsidence whether it is a subsiding basin with compacting-subsiding sediments or a stable basin with compacting-subsiding sediments (RIEKE and CHILINGARIAN, 1974; AUDLEY-CHARLES *et al.*, 1977; FRIEDMAN and SANDERS, 1978; COLEMAN and ROBERTS, 1989; EINSELE, 1992).

Subsidence, because of a subsiding basin and/or compacting sediments after burial by more and more sediments abundantly discharged by the river, is a natural process and inherent in the coastal and delta plains.

River mouths and their coastal plains belong to the group of highly variable depositional environments called *transitional* or *marginal marine* which are controlled by continental and marine conditions (EINSELE, 1992). Hence, coastal plains contain sediments which are continental, coastal and marine. The coastal plains surficially record only terminal geomorphic surfaces, but not the steps necessary to develop those surfaces. These steps are found in the subsurface. The continental, coastal and marine sequences in the subsurface are gradational through estuarine and deltaic facies (COLQUHOUN, 1968).

The very general conditions for estuaries to form are the river mouths where the sediment loads of rivers are small, or where subsidence is taking place faster than whatever quantities of sediment are being delivered to the mouth of the river, or where the tidal range is large and tidal currents are vigorous (FRIEDMAN and SANDERS, 1978), or a combination of these.

The sediment forming the delta is supplied by the river, but the estuary can receive its sediment both from the river and the sea, or only from the sea, or only from the river. It is clear that sediment and sediment supply are the primary factors in determining the distinction between a delta and an estuary. However, this distinction cannot be looked upon as a static feature. River mouths are very dynamic, and they never can be classified into one or another group for their entire geological life span.

How dynamic they are and how they possibly evolve can only be explained when the factors and processes gener-

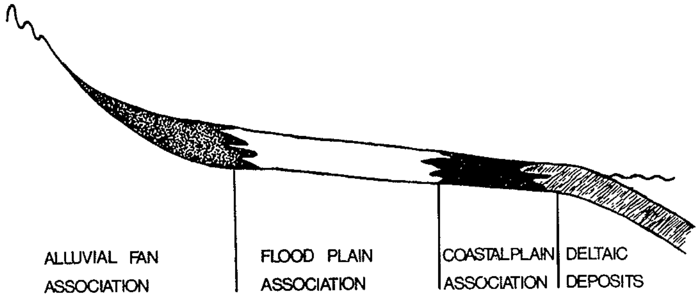

Figure 7. Placement of the coastal plain association into the different types of fluvial associations according to REINECK and SINGH (1973).

ating their formation are known. A very comprehensive summary of the factors has been published by MORGAN (1970); the main topics are discussed here.

Processes and Factors

Sea-Level Fluctuations

One of the major forcing processes in the building up of the coastal accumulation is the change in sea level, generally called *eustatic* sea-level changes, except in specific sea-level research papers.

The concept *eustatic* is commonly used to indicate the global change of the oceanic water level with the emphasis on global and on worldwide simultaneous changes caused by melting of land-based glacier ice (KIDSON, 1986; MÖRNER, 1989).

Since in particular MÖRNER devoted many papers to sea-level changes and their causes (a summary can be read in MÖRNER, 1989), the concept of "eustasy" is no longer tenable because sea-level changes are not worldwide nor simultaneous. However, MÖRNER (1989) preferred keeping the term eustasy, but proposed a broader meaning for it, and redefined the old concept to: "ocean-level changes or absolute sea-level changes, regardless of causation and including both vertical and horizontal geoid changes and dynamic changes". The author illustrates the broadening of the term by depicting a summary of the variables contributing to the eustasy (Figure 8) and a summary of the main factors that control the level of the sea and the land (Figure 9).

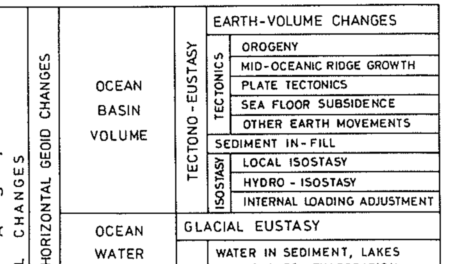

Figure 8. General summary of the eustatic variables (from MÖRNER, 1989).

Whatever the causes, the effect of sea-level fluctuations on river mouth deposits is overwhelming. This has been observed particularly in the sediment record of the present geologic period, the Quaternary.

The best known rate of sea-level change, and the effect of it, is the one that happened in the Holocene Epoch. Sea-level rise in the Holocene is very well documented from both different regions and different coastal settings (VAN DE PLASSCHE, 1986; DEVOY, 1987; CARTER and DEVOY, 1987; FLETCHER, 1988; TOOLEY and SHENNAN, 1989). So well in fact, that it becomes critical to give a general picture of it.

One can still premise that about 18,000 years ago there was a low sea-level stand of about −100 m to −120 m. About 13,000 years ago, sea level began to rise; however, the rate of rise was not constant. Initially, during Late Glacial–Early Holocene, the rate of the sea-level rise was rapid (*e.g.*, 1 m to 1.6 m/century) (DYER, 1986; STREIF, 1989). Sea level reached close to present-day elevation about 5,000 years ago. Areas along the East China Sea recorded higher sea-level stands than present (about +2 m) about 6,000 years ago.

However, the last sea-level rise is but one in a series of Quaternary sea-level fluctuations generating important sediment accumulations from which the preserved record forms the subsurface of the coastal plains.

The response of a river to a sea-level drop is generally described in similar ways by various authors (MORGAN,

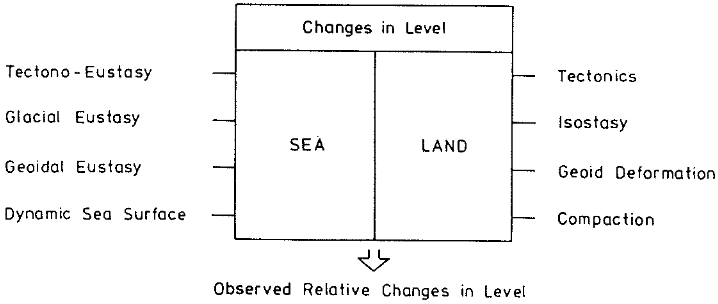

Figure 9. The main factors that control the relative sea level (from MÖRNER, 1989).

1967; BELKNAP and KRAFT, 1977; FRIEDMAN and SANDERS, 1978; DYER, 1986; COLMAN and MIXON, 1988; EINSELE, 1992). As the fluvial system is controlled by its erosional base level, erosion predominates in case of a drop in sea level and a lowered base level. As a result, rivers incise the lower reaches of their courses and discharge large amounts of sediments increasingly further out onto the shelf. Deltas emerge and fluvial channels are cut, dissecting and eroding parts of the delta plain. At the lowest stand of sea level, estuaries seem to almost disappear and are confined to valleys (RUSSELL, 1967; NICHOLS and BIGGS, 1985).

When describing the effect of a low sea-level stand on river mouths, it is remarkable that only the lowered base level and the shifting of the shore zone are emphasized. Besides, nearly all authors state that the rivers deliver relatively coarse sediments.

However, major low sea-level stands happened during glacials, so climatic conditions are different than those prevailing during interglacials. Therefore, changes in vegetation in both drainage basin and coastal plain are to be considered, as these will significantly influence the grain-size distribution of the fluvial system. Changes in the water volume and sediment discharge are to be considered, too, as well as the change in gradient of the river on the newly exposed continental shelf, which generally is an area of low relief and low-angle slope. The latter becomes now a new depositional surface where, depending on the above-mentioned factors, the fluvial system will develop an extensive flood plain, seaward merging with the newly forming coastal plain.

The response of a river to a sea-level rise is much better documented. The Holocene rise, also known as Flandrian Transgression, has been investigated extensively (*e.g.*, BELKNAP and KRAFT, 1977; DEMAREST *et al.*, 1981; NICHOLS and BIGGS, 1985; FREY and HOWARD, 1986; COLMAN and MIXON, 1988; NICHOLS *et al.*, 1991; EINSELE, 1992; CHEN *et al.*, 1992).

As a simplified and evident summary, it can be put forward that in general during a transgression, the shore zone is pushed landward, the bays become infilled and submerged valleys of rivers become buried under sediment. EINSELE (1992) describes in particular the response of deltas to a rapid sea-level rise which leads to extensive coastal retreat on top of the submerging former delta plain. If the sea-level rise does not exceed a few tens of meters, and then persists for some time, the delta front can prograde again as a shallow-water delta.

However, if a general picture is to be given, the response of a river to a sea-level rise or fall can only be put in an oversimplified way. It is true that every river is responding in its own particular way, depending on the various factors such as the eustatic variables and, not least, the amount and size of available sediments.

Although the fact that every river responds differently to sea-level changes and experiences its very own evolution according to many factors, the location of the main river channels remains relatively fixed. At least during the Pleistocene and Holocene, it seems that major rivers reoccupy the same places during various transgressions (NICHOLS and BIGGS, 1985).

Sediment Supply

Sea-level fluctuations might be one of the most important factors in forming and shaping deltas and estuaries and their plains, and the availability of sediment is another overwhelming factor.

The formation and life span of estuaries and/or deltas primarily depend on the balance between the relative sea-level rise and sediment accumulation. Infilling opposes submergence. Where the pace of sea-level rise exceeds infilling, estuaries are well developed and persist. Where the sea level is nearly stable, sediment infilling can catch up to or exceed sea-level rise (NICHOLS and BIGGS, 1985).

A very succinct statement about that was given by FRIEDMAN and SANDERS (1978): "When sea level rises, the deepened valleys become estuaries and, after these have been filled, deltas begin to grow on the more-open parts of the coast".

The balance between the sea-level rise and the sediment accumulation is one of the major causative factors determining whether the river mouth will be a source or a sink and, directly associated with that, whether the coast is prograding or retreating. This process has been well documented by NIEDORODA *et al.* (1985).

If the rate of river sediment input overwhelms the effect of sea-level rise, river mouths become deltas that inject

Table 3. *Sedimentary depositional environments at the different types of river mouths and their coastal plains (dunes are not considered).*

Fluvial-dominated	Mixed Fluvial-wave Dominated
Flood plain	Flood plain
Fresh-water marsh	Shallow fresh-water lake
Coastal peatbog	Lagoon
Shallow fresh-water lake	Fresh-water marsh
Distributary channel	Coastal peatbog
Point bar	Distributary channel
Crevasse splay	Point bar
Levee (subaerial)	Crevasse splay
Mouth sandbar (subaqueous)	Levee (subaerial)
Beach ridge barrier	Mouth bar
Nearshore	Beach ridge (chenier)
	Tidal inlet
	Mangrove swamp
	Tidal flat
	Supra tidal marsh
Wave-dominated	**Tide-dominated (estuary)**
Flood plain	Flood plain
Point bar	Coastal peatbog
Shallow fresh-water lake	Distributary channel
Distributary channel	Elongate subparallel sand ridges
Lagoon	Tidal channel
Beach ridge	Tidal flat
	Mangrove
	Salt marsh

Table 4. *Coastal sedimentary depositional environments at river mouths in relation to tidal range (dunes are not considered).*

Micro Tidal Wave-dominated	Meso Tidal Mixed Wave-tide Dominated	Macro Tidal Tide-dominated
Long barrier island	Coastal peatbog	Coastal peatbog
Beach ridge	Supra tidal marsh	Supra tidal marsh
Chenier	Tidal flat	Tidal flat
Lagoon	Lagoon	Mangrove
	Mangrove	Tidal channel
	Tidal inlet	Subtidal current ridges
	Ebb- and flood tidal delta	
	Short barrier islands	

sediment directly into the surf zone. The beach, bar and shoreface all receive sediment more rapidly than they can exchange it with adjacent environments. In this case, coasts will prograde seaward.

On the other hand, if sea level is rising sufficiently rapidly with respect to the rate of river sediment input, river mouths become estuaries. Estuaries trap not only fluvial sediments, but also sediment from the littoral system. In this case, estuaries and the inner shelf floor become the ultimate sinks for sediments and the primary source is the eroding shoreface, ultimately leading to a retreating or transgressive coast (NIEDORODA *et al.*, 1985).

Thus with progressive infilling, as with the Flandrian Transgression, an estuary changes from a sink for fluvial and marine sediment to finally a source of fluvial sediment for the ocean while sediment accumulation shifts laterally into remaining backswamps, tidal flats or marshes (NICHOLS and BIGGS, 1985).

Whether delta or estuary, the most important fact is that the changes in sediment supply leading to local changes in the depositional environment generate significant changes in the facies of the deposits stacked in the subsurface of the coastal plain.

Sedimentary Environments in Relation to Coastal or Littoral Hydrodynamic Processes

The shape of the river mouth and its adjacent coastal plain is not only controlled by the balance between sea-level fluctuations and sediment input.

The parameters of the marine forces are very important too in determining the sediment pattern, morphology and development of, in particular, the coastal plain. Coastal processes are the major factor in redistributing sediments (from the river, and sediments eroded from subaqueous parts of the delta) and hence in creating the various coastal environments.

Marine energy in the form of waves and tides and coastal currents can produce important modifications at river mouths. Waves attack the shores and nearshore zones of most deltas and redistribute the sediments, while coastal and tidal currents can disperse and transport sediments alongshore over considerable distances from the river mouth, causing extensive accumulation of river-derived sediments downdrift the river mouth (JOHNSON and BALDWIN, 1986; WRIGHT, 1985).

EINSELE (1992) gives a comprehensive summary with an original composite illustration of the influence of wave energy and tidal regime leading to the basic types of river mouths which are: fluvial, mixed fluvial-wave, wave, and tide dominated.

The different shapes of river mouths and their coastal plains in relation to wave energy and tidal regime have been the subject of extensive research (WRIGHT and COLEMAN, 1973; GALLOWAY, 1975; COLEMAN and WRIGHT, 1975; MIALL, 1986). The results, especially the plan view of the different types of river mouths and the triangular diagram, are found in many relevant textbooks (ALLEN, 1978; FRIEDMAN and SANDERS, 1978; LEEDER, 1982; WALKER, 1986; WRIGHT, 1985; ELLIOTT, 1986a; BOGGS, 1987; CARTER, 1988).

The various sedimentary depositional environments which can occur at the river mouths and in their adjacent plains are listed in Table 3 and Table 4.

SEDIMENT CHARACTERISTICS RELEVANT TO COMPACTION

The sediment texture, together with the organic content, forms one of the major parameters determining the geotechnical properties conditioning compaction. However, it would be of no use to indicate the sediment texture for each sedimentary environment.

All relevant textbooks abound with detailed descriptions. A more important reason not to enumerate the sediment characteristics is that the nature of the sedimentary facies depends mainly on the kind and quantity of available sedimentary components, such as sand, mud, organic matter, shells, and fecal pellets (NICHOLS and BIGGS, 1985; FREY and HOWARD, 1986). Tidal channels can be filled solely with sand, or with mud, or with an interlayering of mud-sand-peat detritus, or with sand and large fragments of reworked wood/peat. Intertidal flats can be predomi-

nantly mud, instead of showing the classical tripartition mud/mixed/sandflat, because no sand is available in the littoral system to be redistributed.

Facies can be very much influenced by climate. In humid regions, abundant vegetation is present (mangals occur only between 25° N and 25° S), generating sediments with high organic content or even peat. In arid regions, the supratidal marsh will be replaced by a sabkha.

Biodeposition which may rival physical processes of deposition in intertidal environments (FREY and HOWARD, 1986) is in turn influenced by climatological circumstances (temperature influences bioactivity; rainy seasons determine flood periods and hence salinity, *et cetera*).

Concerning the geotechnical properties conditioning compaction, a fundamental distinction related to the genesis of the deposit is to be made. The sediments that originate as subaerial features are much more consolidated than those formed as submerged features or subaqueous.

In the fluvial system, distinction is to be made between, on the one hand, the flood plain and levee deposits which originate subaerially and, on the other hand, the channel and patterns of deltaic surfaces which initiated as submerged features (RUSSELL, 1967) and which as a result are very compressible. Because of their deposition above the groundwater table, flood plain deposits are overconsolidated and, in the sedimentary sequence, they form stiff compact layers (Figure 10).

This phenomenon is not always evident. In the case of the Shanghai geological setting, a compact, dark green, silty clay layer (DGSC-unit) is described as the keybed at the Holocene–Pleistocene boundary. Most Chinese authors agree that the clay was deposited in a cold and dry period or during the period of last low sea-level stand of the Late Pleistocene. About the genesis of the clay, different opinions are expressed, such as: river-lake-marsh deposits, terrigenous origin, continental deposit with fluvial facies, continental deposit with a well-developed dark ancient soil, traces of the ancient Yangtze river sediments, continental sediments of flood-plain and fresh-water swamps, and finally, windblow loess which through weathering, leaching and compression formed hard clay which then was transformed to a dark green hard clay by dissolving soluble organic matter from penetrating Holocene surface water.

However, the overconsolidation of the clay unit is simply to be explained by its subaerial origin as flood plain clay. Also STANLEY (1990) explains the occurrence of a stiff clay in the Nile delta plain subsurface (at a depth ranging between 15 to 20 m) as evidence of compaction that has occurred in the pre-Holocene sediments. In the stratigraphic description (COUTELLIER and STANLEY, 1987), the stiff clay is interpreted as being deposited in subaerial conditions, from deltaic origin, probably in swamps, during the last major interglacial. The stiff clay is directly covered by transgressive sand, deposition due to the Holocene sea-level rise. In 1992, CHEN *et al.* interpret the stiff clay as flood plain muds of overbank origin. Also, here the stiff clay layer in the Nile delta sequence is most probably interpreted as flood-plain clay, deposited during low sea-level stand when the flood basin of the Nile was well developed and extended far onto the present shelf. Therefore, it is overconsolidated, and it did not particularly experience more compaction than all the other sediments.

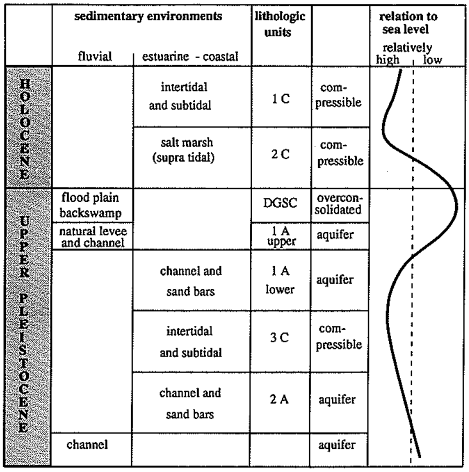

Figure 10. Stratigraphic sequence of the Shanghai subsoil (upper 70 m) where the classification is based on sedimentary environmental interpretation yielding relevant units for the geotechnical and hydrogeological parameters.

Compaction affects all sediments, but is most pronounced in fine-grained sediments, such as silts and clays. The factors that influence compaction in sands are mostly shapes and sorting of particles and depth of burial. During compaction, sand particles respond by shifting into more dense packing arrangements; hence, porosity decreases. Angular and poorly sorted sands are more compressible than rounded and well-sorted sands.

Backswamp areas produce deposits with high organic and moisture contents. Peat (low density organic accumulation) from coastal swamps and mangroves can grow in conditions where the water content may be 500–1,000% (HAWKINS, 1984). Consequently, peat can be subjected to extensive consolidation.

Peat is the most compressible of all natural sediments because of its high porosity and its weak skeletal framework of vegetable fiber. Not only will it compress beneath an applied load, but, under certain conditions, it will also compress under its own weight, a process which is called autocompaction. Peat shows a unique behavior with respect to consolidation. One of the reasons is the more rapid reduction in permeability with change of volume as compared with clay. Another reason is the loss of volume with decomposition and the complex physiochemical changes that go on all the time and that have a continuing effect on the structure and strength of the peat fabric (KAYE and BARGHOORN, 1964; HAWKINS, 1984). Geotechnical and hydrological properties of peat are extensively discussed by HOBBS (1986).

All intertidal and subtidal deposits have a high moisture content and are very compressible. Moreover, the sand deposits are characterized by loose packing, except beach deposits, because of the action of breaking waves.

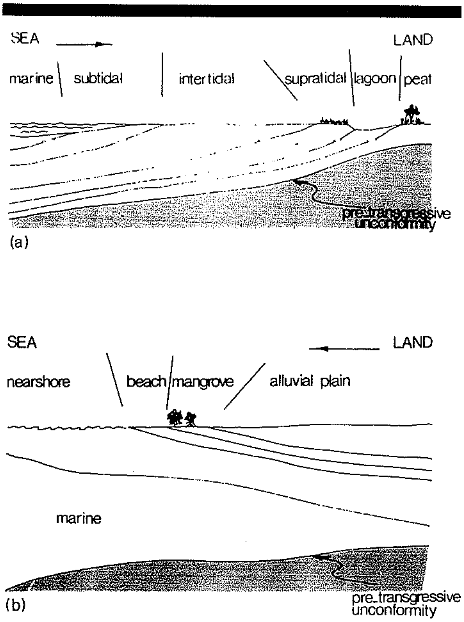

Figure 11. Schematic representation of (a) a transgressive and (b) a regressive stratigraphic sequence according to Walther's Law of Facies.

Another distinction is to be made between sand-filled channels from, on the one hand, the fluvial dominated system and, on the other hand, the tidally dominated system. Young tidal channels bear loosely packed sand with a high water saturation. A sudden decrease of internal pressure (most frequently by earthquakes) causes liquefaction, resulting in local land subsidence.

Overconsolidated layers in the Holocene coastal sequence are very rare. They never had the occasion to dewater in a natural way. However, when, during the Holocene infill, relative sea level has dropped, sediments of few meters in thickness can be overconsolidated because of desiccation (GREENSMITH and TUCKER, 1971). Desiccation can cause consolidation of tidal sediments when the deposits remain above the normal groundwater level. In such a situation, the water is removed by direct evaporation, by capillary action, and by plant disturbance causing rearrangement of the fine particles and reducing porosity (HAWKINS, 1984).

Such an initiation of physical ripening, generating a typical crumbly structure, is often found in salt marsh (supratidal) deposits. But in extended great delta plains characterized by subsidence (due to tectonic setting and/or natural compaction of the deeper deposits) and/or by a deficiency of deposition on the marshes, the groundwater table always remains close to the surface. Such a situation is likely to evolve into the development of a coastal peat-bog.

In reclaimed areas where drainage and groundwater table are controlled by men, the upper few meters are overconsolidated because of desiccation forming what is called the crust.

THE ELABORATION OF GEOMETRY

Modern coastal or delta plains bordering the lower reach of major rivers are built up by the fine-grained clastic deposits and organic sedentary units generated by the various fluvial and coastal depositional environments which have been migrating laterally under the influence of the interaction between sea-level fluctuations, sediment supply, hydrodynamic processes and tectonic setting.

In view of the many factors interacting and contributing to the final depositional record, it is self-evident that the resultant vertically stacked succession of the deposits is characterized by frequent lateral and vertical facies changes. However, rivers with overwhelming sediment supply generate much more homogeneous sedimentary units with extended lateral continuity than rivers where hydrodynamic processes predominate at their mouth.

Establishing the geometry of the various facies in the depositional body of a coastal plain requires an enormous amount of data. And as is self-evident, the more data available, the more accurate the delineation of the geometry will be.

Modern coastal lowlands, however, offer no (natural) outcrops. All data have to be acquired by means of boreholes (cores) and various geophysical loggings. But the amount of drillings and loggings is not infinite; the delta plain, on the contrary, is so endlessly vast! Moreover, one should always be very well aware that a borehole (logging) shows the record of just one single spot in a complex mosaic. There exists no such thing as a boring representative for an entire area.

In order to obtain a three-dimensional picture (as complete as possible) of the complex mosaic of the subsurface of the depositional body, every core is to be interpreted. This interpretation is to be put into larger context by means of cross-sections (CANT, 1986). The various distinct and significant units from the boreholes (loggings) must then be correlated; filling in the blanks between the data points remains the ever critical decision!

Correlating boreholes is not just a simple line-drawing act. It involves the knowledge of the interplay of all the relevant factors and processes that built the depositional body.

Therefore, facies from depositional environments form excellent correlatable units (BAETEMAN, 1987). However, in order to interpret facies of a depositional system which consists of an assemblage of interrelated environments and their associated processes, it is necessary that facies be analysed in terms of their spatial relationships. Coastal plain systems, as well as rivers that feed them, form an excellent example of an interrelated depositional continuum (KRAFT and CHRZASTOWSKI, 1985).

Furthermore, it is often impossible to make a unique environmental interpretation on the basis of a single depositional facies. Therefore, facies associations and sequences must be studied rather than individual facies. Facies associations are groups of facies that occur together and are genetically or environmentally related. The sequence in which they occur thus contributes as much in-

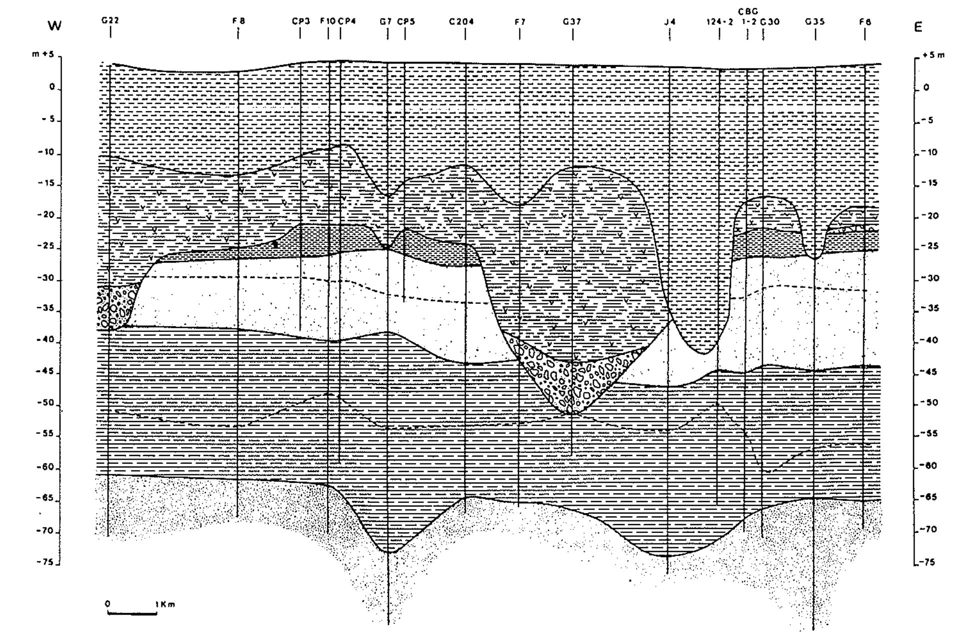

Figure 12. Example of a cross-section from the northern part of the Shanghai area revealing the detailed geometry of the relevant units. Such a cross-section forms the basis for the discretization of the units resulting in the quantitative data of the geological conditions necessary for the mathematical model. This cross-section clearly shows the discontinuity of the impermeable flood-plain clay (DGSC-unit) as a result of erosion.

formation as the facies themselves (BOGGS, 1987; READING, 1986; WALKER, 1986, 1990).

The concept involved in the facies associations is the application of a principle known as Walther's Law of Facies, stating that, where there are no time breaks in a stratigraphic section, those sediments which were laterally adjacent must succeed each other vertically (VISHER, 1965).

VISHER (1965) developed this concept, emphasizing the sedimentary process producing a sequence of environments. The author stated as a starting point that "it is rather the sedimentary process that is both the unifying and most readily identifiable feature in a sedimentary sequence. Therefore, the sedimentary process permits not only a description of the vertical profile, but also an understanding of the mechanism of its formation. Each fundamental sedimentary process produces both a specific environmental distribution and a specific vertical profile". KRAFT and CHRZASTOWSKI (1985) give a detailed discussion of the application of Walther's Law in coastal environments.

Figure 11 shows a model of an idealized transgressive and regressive sequence based on the specific order of succession of the sedimentary facies. A regressive sequence is built up with an advancing or prograding (progradational) coast; a transgressive sequence with an erosional shoreface regime and a predominance of submergence. An aggradational (aggrading) sequence has been defined for a stabilized position of the coast (GALLOWAY, 1986; FRIEDMAN and SANDERS, 1978).

Such sequences based on the vertical and lateral facies relationships form an excellent framework in which all relevant factors and processes of coastal development can be integrated. Therefore, they are forming a firm basis for the interpretation of the individual core (logging) and their correlation. However, vertical sequences only represent a summary of the very local setting; they are in no way representative for the entire depositional body.

Sedimentary environmental interpretation and sequence analysis can be successfully applied for the interpretation of individual cores and the elaboration of their correlation aiming at the geometry of the distinct facies (Figures 12, 13 and 14). The knowledge of the interaction between the major factors and processes justifies the extrapolation of comparable facies (and helps to fill in the blanks).

However, one must always be on the lookout that the interpretation and correlation must be done in a way as detailed as possible. Before significant contacts and distinct facies are interpreted and defined, every subtle change in characteristics in the sedimentary record is of importance. This is especially the case in environments where laterally restricted sediment bodies are occurring frequent-

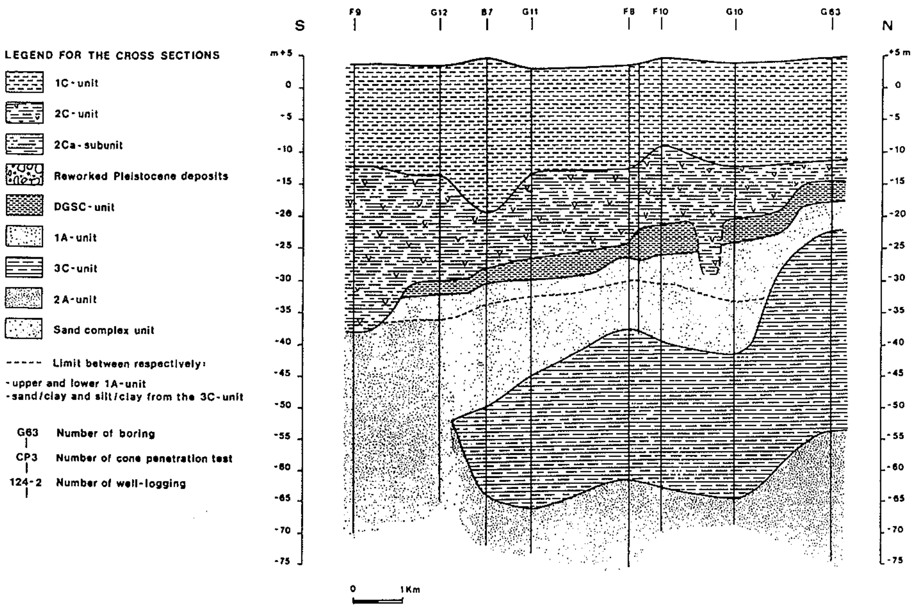

Figure 13. Example of a detailed cross-section from the Shanghai area showing steps in the topography of the flood-plain clay due to the process of river avulsion. The cross-section clearly demonstrates the thinning of the compressible 3C-unit towards the south and the convergence of the two aquifers (1A and 2A). The absence of the compact impermeable clay unit in the south indicates a critical situation: the thick compressible Holocene units are in direct contact with the aquifers, so that in case of groundwater withdrawal, leakage and hence compaction is guaranteed. (From BATEMAN and SCHROEDER, 1990.)

ly; *e.g.*, sand-filled channels surrounded by mudflat facies. From a geotechnical point of view, the two facies differ significantly. If in the available data a channel fill has been recovered in only a few cores, its lateral extension must be drawn anyway. In that case most of the time, additional indications are found in the adjacent boreholes; one only has to learn to recognize, interpret and evaluate the subtle changes.

Detailed cross-sections also implies that all available data must be used. Experience has taught that data not directly fitting into the picture of the cross-section are likely to be omitted!

THE STRATIGRAPHIC SEQUENCE

The stratigraphic sequence of coastal plains exhibits a rich record of the changes in the main factors and processes that happened for the past one hundred thousand years.

Such a record contains in particular features related to both maximum and minimum sea-level stands. These features are not to be translated into oversimplified *transgressions* and *regressions* whereby the landscape is instantaneously and completely submerged, then emerged, respectively.

Even when sea-level rise (or fall) is rapid, all sedimentary environments, fluvial as well as coastal, as a rule re-adapt continuously to the new situation(s). Such continuous adaptation generates various facies in the subsurface and creates an even more complex mosaic of all coastal and fluvial facies. This mosaic is to be unravelled too.

It is necessary to stress the fact that several Pleistocene transgressions do not have the same lateral extension which, moreover, is certainly not identical to the Holocene one.

All the facies will not necessarily be preserved in the sequence, although it would not be correct to assume that only records of regressive sequences have a good preservation potential, and that sea-level rise removes the deposited transgressive record (KRAFT and CHRZASTOWSKI, 1985).

Taking the preservation potential into consideration, the coastal stratigraphic sequence of the coastal and delta plain is in general composed of an alternation of fluvial-dominated vertical sequences and coastal-dominated vertical sequences, built up at low sea-level stand and high sea-level stand, respectively.

In the coastal vertical sequence, deltaic deposits overlie marine strata in a regressive stratigraphic sequence; although in a transgressive stratigraphical sequence, the lower reaches of every large modern river contain estuarine sediments that have been deposited during the submergence (FRIEDMAN and SANDERS, 1978).

Coastal vertical sequences may also begin with a basal transgressive sand or basal transgressive peat. Such a sequence usually is bounded at the base by a pre-transgressive unconformity formed by fluvial aggradation (flood-

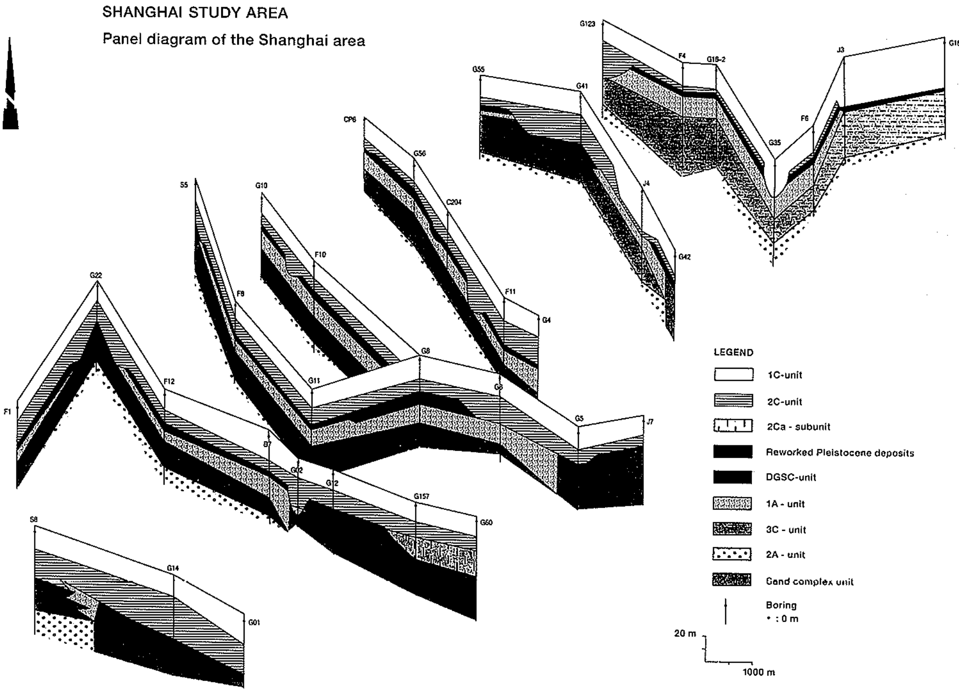

Figure 14. The elaboration of geometry always requires the construction of panel diagrams because they demonstrate the ultimate possibility in the interrelation between the cross-sections and they give the general overview of the spatial extension of the relevant units.

plain clay, levee sand, channel fill) or, in those areas where these deposits are not present anymore, formed by fluvial erosion at the lowered sea-level stand or at the initiation of the next coming sea-level rise, when, because of climatic amelioration over the entire drainage basin, the river is characterized by renewed activity.

The bulk of the coastal vertical sequence is then formed by an amalgam of facies deposited in coastal environments. The thickness of the vertical sequence can never exceed the relative sea-level rise of the transgression (NICHOLS and BIGGS, 1985). That is why estuarine environments might prograde over adjacent marine environments once they are filled. If the effect of sediment supply exceeds the relative sea-level rise, the estuary will fill and finally inject fluvial sediment directly into the marine environment (NICHOLS and BIGGS, 1985), and the river becomes able to prograde actively, *i.e.*, forming a delta. Estuaries are indeed very ephemeral features, geologically speaking; the coastal vertical sequence ultimately evolves into an alluvial flood plain.

Definitions, explanations and comments on facies and sequences are given by the leading facies analysts READING (1986) and WALKER (1986, 1990). Excellent examples of facies analysis and models in coastal environments are discussed by ELLIOTT, 1974, 1986b; BOOTHROYD, 1985; IMPERATO *et al.*, 1988; FREY and HOWARD, 1986; DALRYMPLE *et al.*, 1990; SHA LI PING, 1990; YANG CHANG-SHU, 1989.

The recognition of the different stratigraphical sequences which arrange the various facies into a specific orderly succession is of great help for the determination of the sediment characteristics conditioning compaction.

Depositional environmental interpretation and vertical sequence analysis are the most important tools in determining the three-dimensional geometry of coastal sedimentary facies. Hence, the general record of events can be identified, and eventually the development of the coastal plain in space and time can be delineated.

CONCLUSION

Because of their favorable geographical location, coastal plains support high population concentrations and megacities where the demand for fresh water is high.

Many of these cities have already experienced severe land subsidence caused by groundwater withdrawal. Land subsidence in some of these cities is under control today; however, metropolitan areas particularly in the Third World continue to pump groundwater in a rather uncontrolled manner, aggravating the critical situation of subsidence.

Proper groundwater management can resolve this man-induced phenomenon, but only when it is based on a profound geological study aiming at the determination of the three-dimensional spatial distribution of distinct deposits, each bearing their particular geotechnical and hydrogeological properties. The elaboration of the geometry calls for the knowledge of the processes responsible for the deposition of the sediments and the formation of their facies, thus making an environmental interpretation.

Coastal plains along major rivers consist of a body of sediments which are not the result of just one single fill sequence. The areas are pre-eminently environments where at one time coastal processes dominate and at another fluvial processes show an overwhelming activity.

These plains developed, at least during the Quaternary, during several successive high stands of sea level when coastal-dominated vertical sequences were generated, separated by fluvial-dominated vertical sequences formed at low sea-level stand.

The channel, bar and levee deposits from the fluvial-dominated sequence form the aquifers. The flood-plain deposits because of their particular genesis form stiff impermeable overconsolidated layers, which at the same time, represent the sole units in a coastal plain sediment body having a significant bearing capacity. Conversely, deposits from the coastal sequences are not consolidated, hence they are very sensitive to compaction.

A profound study of land subsidence implies that geological, geotechnical and hydrogeological research should complement each other continuously. The geological data, however, form the basic framework. Only such an approach yields the badly needed accurate quantitative information about the variables involved in land subsidence. These parameters will then form the basic data for the design of a mathematical model—the ultimate tool for groundwater management and land subsidence control.

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Improved Use of the Fluidized Bed Dryer for *Artemia* Cysts

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ABSTRACT

A fluidized bed dryer for processing Artemia *cysts at temperatures above 40°C is described and evaluated. The design is directed towards electronic temperature regulation and optimal design of the drying unit. The described fluidized bed dryer proves to be reliable for cyst processing, using inflow air temperatures up to 90°C. The use of this elevated temperature ensures a higher drying rate, resulting in a drying capacity more than 4 times higher than when using inflow air of 40°C. Electronic temperature regulation resulted in a large flexibility of the temperature regime inside the drying unit.*

INTRODUCTION

Proper processing and drying of *Artemia* cysts is of crucial importance to obtain a storable product with maximal hatching quality. The different processing steps of cleaning, dehydration and packaging of the cysts have been described in detail by Voronov (1974), Rakowicz (personal communications) and Sorgeloos *et al.* (1986). With regard to dehydration of the cysts, the drying rate, drying temperature and the final water content of the cysts appear to be the most important factors affecting the hatching quality of the cysts.

Godeluck (1980), Vanhaecke and Sorgeloos (1982) and Vanhaecke (1983) investigated different drying methods and showed that the drying rate has a significant effect on the hatching quality of the cysts. A slow drying resulted in decreased hatching efficiencies as well as in a delay of hatching after storing the cysts for more than 1 month.