

Feature

Sinking cities

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When water supplies are abstracted from alluvial sands, interbedded clays compact and cause ground subsidence. Entire cities are being gently lowered, with serious consequences for those on low coastal sites.

Ground subsidence is often seen as the poor relation in the family of geohazards, perhaps because it rarely incurs a death toll. It can have spectacular moments, when ground collapses into caves or old mines, but slow, creeping subsidence on clay can never achieve levels of the visually dramatic. Yet clay subsidence can cause entire cities to go down and can damage thousands of buildings. In many countries, the total costs of subsidence damage equal or exceed those from landslides or earthquakes.

Except for tectonic deformation, all subsidence is due to the presence of holes in the ground, as these constitute somewhere for the ground to move down into. The holes may be big, in the case of caves and mines, or they may be small – the pore spaces between grains of a sediment. Sand is porous but causes minimal subsidence because its quartz grains are strong enough to resist the deformation that has to accompany the reduction in void space. But clay is also immensely porous, and its grains of weak clay minerals are easily deformed as voids close up, volume decreases and the ground goes down.

Clay compacts because of either (or both) increased load upon it or reduced support within it. The load may be imposed in the form of buildings (such as the Leaning Tower of Pisa) that subside under their own weight on inadequate foundations. Or it may be by self-weight, when clays compact beneath thick piles of later sediment – the natural subsidence that occurs in all deep sedimentary basins. Partial support within a clay is provided by water between the mineral particles; this is pore-water pressure, and it is critical to the subsidence story. Remove all or some of the water, and the unsupported clay compacts. On a small scale, tree roots can suck water from a soil during a dry summer and cause the corner of a single house to subside. On a larger scale, abstraction of groundwater to supply a city can cause the whole city to subside.

Nobody pumps water from clay; its permeability is too low. But sands form excellent and productive aquifers, and are typically interbedded with clays within thick sequences in sedimentary basins. These basins provide level ground, ideal for urban growth, and the buried sands provide the necessary water resources. Pump the water from the sand, and water from the

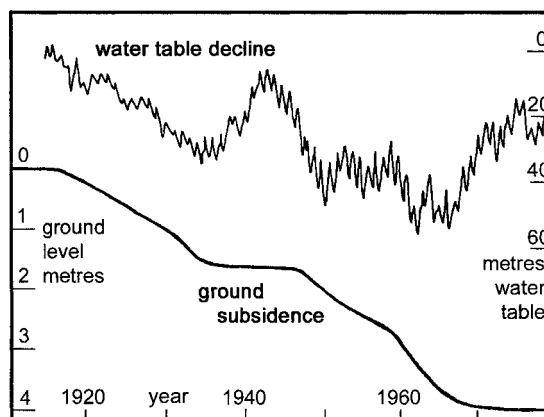
adjacent clay will then very slowly flow into it, to regain the hydraulic equilibrium. So abstraction reduces pore-water pressure in the sand, which is followed by reduced pore-water pressure in the clay, which causes subsidence. The chain reaction is inevitable, and this is therefore subsidence induced by man.

Santa Clara

At the southern end of California's San Francisco Bay, the Santa Clara Valley is well known as Silicon Valley because of its wealth of computer industries. It is also famous as the first site where clay subsidence was recognized as being induced by man's own activities – where the simple correlation between falling water tables and falling ground levels became all too clear (Fig. 1). From about 1920, water tables in the various sand beds beneath the valley floor went into steady decline. This was partly due to a spell of low rainfalls, which reduced the natural recharge, and partly due to increased abstraction, as industry spread across the valley. In less than 20 years, water tables fell by about 35 m, and the valley floor subsided by nearly 2 m. Then the subsidence stopped, because water tables recovered through a series of wet years.

Subsidence only restarted (in 1948) when the water tables declined below the previous low point, and it grew steadily worse through the 1960s. All the ground survey data and the well records were put together (Fig. 1), and the cause of the sea's advance into the subsided valley was recognized. The response was simple, but expensive. Licenses for groundwater pumping were cut back, new pipelines were built to bring surface water from the Sierra Nevada rivers, and excess pipeline water, during the spring snowmelt, was poured into the old wells. The aquifers recovered, and the subsidence stopped,

Fig. 1. The decline of water-table level correlated with ground subsidence in the Santa Clara Valley, California. The water-level data are taken from a single monitored well, which therefore has the small annual fluctuations superimposed on the longer trend.





although the land was already 4 m lower than it had been originally. The lessons of Santa Clara were learned worldwide.

Los Angeles

A city beset by all manner of geohazards, Los Angeles has its clay subsidence, although this affects just a small part of it. The Long Beach harbour area sits in a bowl of subsidence in which the centre has sunk by 8.8 m. In true Californian style, this was due to abstracting not groundwater but oil, although a lot of water came out in the same process. The result was the subsidence bowl, directly over the compacting sedimentary rocks in the Wilmington oilfield, and the harbour area sank so much that massive dykes had to be raised to prevent inundation of the land between the shipping bays (Fig. 2).

When oil was pumped freely, during the primary phase of field production, fluid pressures in the

Fig. 2. Embankments protect the dry land that has now subsided below sea level in the Long Beach harbour area. Still pumping are the oil wells that were the initial cause of the subsidence.

Fig. 3. A massive gate ready to seal the floodwall to protect the city of New Orleans since it has subsided on the compacting sediments of the Mississippi delta.

ground declined and caused the subsidence. Fortunately, a secondary phase of oilfield development involved injecting water down some of the wells in order to drive the oil out through nearby production wells. In the 1960s, this re-pressurized the oilfield, and stopped the subsidence. Furthermore, the ground went back up as soon as the amount of water injected exceeded the amount of oil previously extracted. However, the total ground rise was less than a half a metre, and this was due to the elastic rebound of the oil reservoir sandstones. Compaction of the adjacent de-watered clays had caused most of the ground subsidence, and clay compaction is almost completely inelastic. Clay subsidence is largely a one-way process, and cannot be recovered; there is no rebound.

New Orleans

Any city that stands on the coast is particularly sensitive to subsidence. New Orleans has subsided so much that nearly half the city area is now below sea level, some parts by as much as 2 m. Most of this is due to natural compaction of the hundreds of metres of clay-rich sediments that form the Mississippi delta. The whole delta top is subsiding by about 8 mm/yr, although part of this is due to crustal sag under the weight of the sediment. A small part of the subsidence is due to compaction of really soft peat soils in some areas, and also by groundwater pumping (although this is to enable essential land drainage and is not just for water supply).

The end result of this inevitable compaction of the Mississippi sediments is that New Orleans now has a much increased flood hazard. The city is almost surrounded by levees and walls. Gaps in the walls are mainly for access to floodway carparks, but can be sealed with massive gates ahead of any predicted flood (Fig. 3). The main danger is not from the river, as floodwaters can be diverted into the Atchafalaya Floodway before they reach the city, but from tidal storm surges on Lake Ponchartrain, immediately to the north. These are also inevitable, and much of New Orleans is now so low that it would not be built today.

London

Subsidence on the clay beneath London has been only modest. Because it is of Eocene age, and has already been consolidated by cover sediments since removed by erosion, the London Clay has very little potential compaction. Its pore-water pressures have, however, fallen massively, in equilibrium with the declined water table in the over-abstracted chalk aquifer that underlies it. Induced ground subsidence has reached over 300 mm in the Chelsea region, but is less away from there. This subsidence has now been



greatly reduced, as water pressures have largely recovered since pumping from the chalk has been more carefully controlled.

The greater problem for London has been the tectonic deformation that is still causing south-east England to subside by about 3 mm/yr (while north-west Britain is rising), at the same time as sea level continues to rise at about half that rate. It is these two unstoppable factors that necessitated construction of the Thames Barrier, which should prevent flooding of London by high tides until about the year 2130. After that, a higher barrier will probably be needed.

Venice

Surely the most famously subsided city in the world, Venice has not gone down as much as many other cities, but it did start from a critically low level on the mud islands amidst its lagoonal marshes. The canals were part of the original design, with the Grand Canal along a splendid meander of a natural channel. But the beautiful piazzas and the network of walkways were above water level – until they were subjected to regular tidal flooding since the entire city has subsided (Fig. 4).

The subsidence of Venice is a classic, because so many factors are involved (Fig. 5). The site lies on the edge of the huge deltaic wedge of Quaternary sediments from Alpine rivers, now dominated by the River Po. Under Venice, the sediments are about 70% clay, are over 500 m thick, and are all compacting under self-weight, causing natural subsidence at a rate approaching 0.5 mm/yr. As a result of global warming, and the consequent melting of glaciers and icecaps, sea level is rising at rates that have kept between 1.2 and 1.5 mm/yr throughout the last century. If global warming accelerates, either naturally or exacerbated by man's impacts, this factor may increase more rapidly, but there is, as yet, no sign of accelerating sea-level rise at Venice, where it is carefully monitored. These two natural factors have

Fig. 4. (below left) Piazza San Marco in Venice, totally flooded during one of the all-too-frequent 'aqua alta' events.

Fig. 5. (below right) Graphical representation of the causes and effects of the subsidence of Venice. The bar graph shows the number of aqua alta events higher than 1200 mm in each 5-year period.



caused Venice to subside by about 150 mm in the last 90 years (Fig. 5), and there is every sign that this rate has been roughly maintained since the city's major development 500 years ago.

Unfortunately, extra subsidence has been induced by groundwater abstraction that started around 1920 to supply the Marghera industrial complex (at the landward end of the lagoon causeway). After 50 years of pumping, water table decline had reached 10 m under the centre of Venice, where it caused an additional 120 mm of induced ground subsidence. Both figures were greater at the centre of pumping at Maghera, but had no serious impact on the modern structures sited on higher land. Excessive groundwater abstractions were stopped by about 1970, and water pressures therefore recovered. The effect was nearly 20 mm of rebound uplift for Venice. This was the source of press reports that have appeared ever since about Venice now being on the rise. Sadly, the rebound was all over within a few years. Now there is also a possibility of a new phase of induced subsidence due to planned extraction of natural gas from anticlinal reservoirs in Pliocene sands 1000 m down beneath the Adriatic. Gas reservoirs have already been found less than 20 km south of Venice. The impact of their exploitation would appear to be negligible, but there is room for debate until the geology is better assessed, and some concern may be justified.

The impact of all the subsidence has been the increasing frequency of 'aqua alta' events. These are the periods of high water, when many of the streets, piazzas and ground floors of buildings are flooded. An aqua alta is a tidal flood that normally lasts only a few hours over the high tide. But the flood levels depend on a host of features. They are highest on spring tides; water only reaches about 400 mm above mean sea level on a neap tide, but an aqua alta is defined as a level more than 800 mm above mean, when low areas, including Piazza San Marco, are flooded. A cyclonic weather system can allow sea levels to rise an extra 300 mm, simply due to the reduced

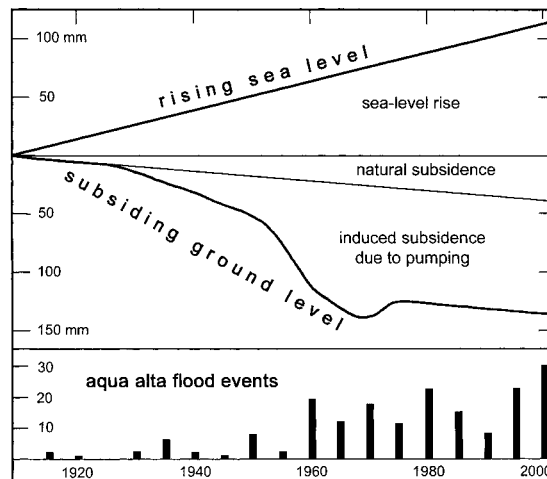




Fig. 6. (above) Boardwalks across the end of a flooded Piazza San Marco.



Fig. 7. (right) Branchline boardwalk into a flooded shop in a subsided Venice.

atmospheric pressure not holding the water down. A scirocco wind from the south-east can push water along the Adriatic and raise the level at Venice a metre above normal tide level. The levels of the rivers draining from the Alps also contribute. Combine these features and the result is a serious aqua alta (Fig. 6). They never occur in summer, and November is the peak month. Although major floods were rare before 1900, the newly subsided Venice usually has 4–6 events per year, when water levels exceed 1200 mm (Fig. 5) and large parts of the city are inundated.

The Venetians have learned to live with the aqua alta. Every winter, from September to April, raised boardwalks are installed through the city streets (see front cover). They create a network of dry routes at the 1200-mm level, linking all the main buildings and ferry stops. The hotels and larger shops have their own branch boardwalks leading inside their buildings (Fig. 7). Furniture is temporarily moved, and the lower shelves are cleared in the shops. An aqua alta is predictable, and sirens give advance warnings when water level will exceed 800 mm, with back-up information on phone lines, notice boards and a website. Those who live, work or shop away from the boardwalks, paddle. A smartly dressed lady changing from high heels into wellington boots, before stepping off the boardwalk to wade to a shop, is a regular sight.

Rescue plans for Venice have been talked of for decades, but progress is slow in Italian politics. The current plan is to install Thames-style moveable barriers on the three entrances to the lagoon, so that they can be closed to keep out the major high tides (which reach so high that they damage the structure of the buildings). Costs will be around £1500 million, and the scheme is opposed by those concerned more for the environment of the lagoon. The alternative of a permanent ring dyke around the entire city is not in

favour, as water quality in the Venetian canals relies on tidal flushing. Similarly, cheaper fixed barriers on the three lagoon exits would cut the natural drainage and tides of the entire lagoon; they are not an option. In order to need barrier closures only for the highest aquae altae, the rims of key islands (i.e. blocks of houses between canals) will be permanently raised by about 200 mm to keep out the lower levels of flood. This will entail rebuilding most of the drains to prevent back-flooding into the piazzas and buildings, and the entire floor of flood-prone Piazza San Marco will also be raised. These extra items will cost another £30 million – subsidence is expensive!

Mexico City

The amount of subsidence induced by a given amount of water table decline is partly a feature of the clay's age. The soft young clay beneath Venice is more unstable than the stiff old clay under London. But it also depends on the clay type. The least stable clay is one rich in montmorillonite (part of the smectite group), which is formed mainly by tropical weathering of volcanic rocks. So there is little of it under London, but it is dominant under Mexico City, which has spectacularly bad subsidence problems.

The soft clay is 450 m deep in the old lake basin, on which now stands the heart of Mexico City. Unfortunately, it is interbedded with sands, and these are

such good aquifers that have they been heavily over-abstracted for water supply. Subsidence was inevitable, and from 1947 to 1957 most of the city centre was subsiding at a rate of nearly 300 mm/yr. Total subsidence in many parts of Mexico City now exceeds 9 m. There is obviously no threat from coastal flooding, but differential movements have damaged many structures. Controls on pumping groundwater from the shallow aquifers have now reduced the regional subsidence rate, but there are still problems with heavy buildings.

With soft clay at the surface, engineers know that any building can subside. The Palace of Fine Arts was built on a massive concrete raft, so that it would not be damaged by subsidence, but it has sunk 3 m below street level (this is in addition to the 9 m that the streets and the building have subsided together). In contrast, buildings that are founded on piles bored down to beds of sand have remained almost stable. But the streets around them have fallen to lower levels because they stand only on the clay that is compacting as it is dewatered (Fig. 8). So some buildings are founded on piles to lesser depths, so that loading compaction of the lower clays matches dewatering compaction of the upper clays (Fig. 8). With this innovative engineering design, these buildings actually have their front doors at street level.

Meanwhile, steel casings in the deeper water wells are the structures anchored to the deepest (and most stable) layers of sand. So they have stood completely still while the clays through which they pass have compacted in response to their secondary dewatering. The ground has simply subsided around the well casings, which now protrude 4 or 5 m above ground level in some of the city squares. Regardless of the



Fig. 9. The Shanghai Bund, now subsided to below river level at high tide.

variable state of the buildings around them, the well casings are among the most dramatic demonstrations of the regional subsidence that besets so many cities.

Shanghai

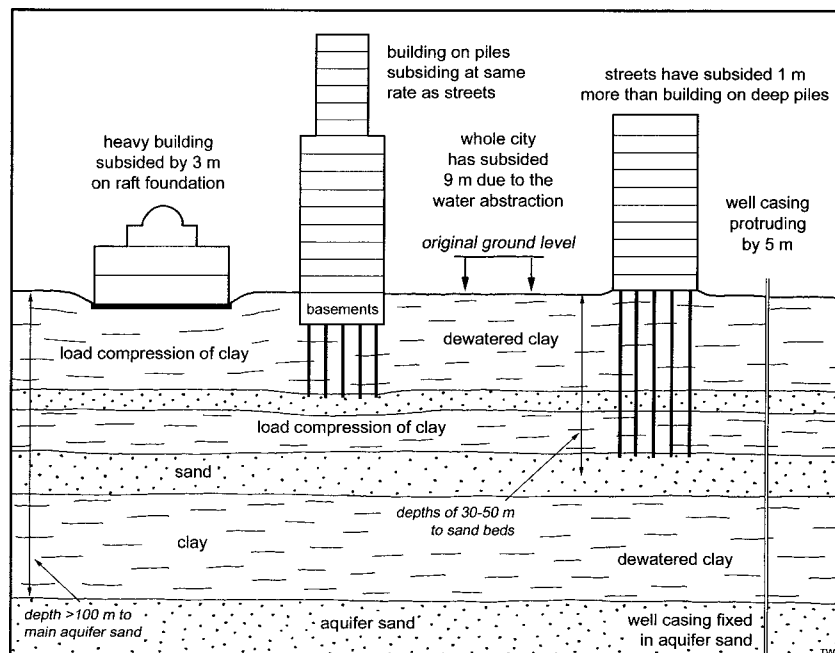
Most Asian cities are built on flat land on either alluvial or coastal sands and clays. With traditions of water abstraction from convenient shallow sand aquifers, the repeated records of clay subsidence are hardly surprising. Shanghai is no exception. The downtown area had subsided 2.63 m in the 45 years up to 1965, when controls on well abstractions were introduced. Since then, there has been a short phase with nearly 0.03 m of rebound, followed by a return to much slower subsidence, which is partly due to natural clay compaction as in the Venice model. The original heart of Shanghai was around the great trading houses built along the riverside Bund, and this is still the smart office address looking out over the tidal river harbour. A bund is a meant to be an imposing embankment, but the subsidence has reduced the Shanghai Bund to a level that is now below the river at high tide (Fig. 9), and the popular walkways and gardens are protected from flooding by new walls.

The Shanghai story is matched in so many other cities in eastern Asia. Tianjin, Osaka, Niigata and Nagoya have each subsided more than 2 m, Hanoi, Taipei and Jakarta have achieved only lower values, and parts of Tokyo have gone down by more than 4 m. But water controls have now greatly reduced the rates of subsidence in all these cities.

Bangkok

Current record-holder for the rate of subsidence by an entire city appears to be Bangkok. About four million people live within about a metre of sea level, and

Fig. 8. Diagrammatic cross-section (not to scale) through streets and buildings in Mexico City that are subsiding at different rates on the clay ground.



subsidence has already reached 1.0–1.5 m across much of the city. It's nearly all due to the 15 000 wells that take more than 1000 000 m³ of water every day out of shallow sand aquifers that receive far less natural recharge. Inevitably, this causes compaction of the interbedded clays, mostly within those less than 50 m deep. Until resources are found to provide an alternative water supply and close down the wells, the subsidence continues, at rates reaching 100 mm/yr in some areas.

The effect is an enormous increase in flooding across the city, partly by water from the main river and partly by rainfall that cannot drain away. Sandbags are now a feature across many of the access ways to the Chao Phraya river (Fig. 10), but rain-storm flooding cannot be stopped. Huge areas of the Bangkok suburbs are inundated on a regular basis, to greater depths, and for longer periods than ever before. In these areas, endless houses are fitted in between various industrial and commercial sites, which include some crocodile farms. During a major recent flood, water levels were so high that many of the giant reptiles escaped. They went off to roam the suburban canals and gardens, and the city had to offer a bounty for any that could be recaptured. As the scale of the flood was due to the subsidence, the predatory crocodiles could probably count as the most bizarre of secondary geohazards.



Suggestions for further reading

- Barends, F.B.J., Brouwer, F.J.J. & Schroeder, F.H. (eds), 1995. *Land Subsidence*. International Association of Hydrological Science, Publication 234 (IAHS,00 Wallingford). 492pp.
- Waltham, A.C., 1989. *Ground Subsidence*. Blackie. 202pp.

Fig. 10. Sandbag flood barriers beside the river in Bangkok, where problems will continue to worsen while the city continues to subside.