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Effects of Soil on Structures

Influence du sol sur les structures

Einfluss des Bodenverhaltens auf Bauwerke

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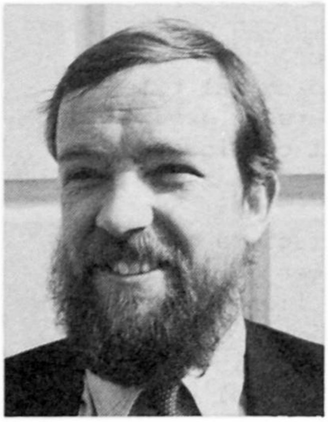

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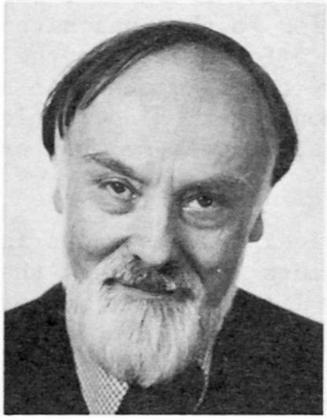

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SUMMARY
This paper deals with events in the ground which affect structures in ways which may not always be foreseen. It includes many examples of actual or potential damage.

RÉSUMÉ
Cette communication traite des phénomènes dans les sols ayant des effets sur les structures, qui ne peuvent pas toujours être prévus. Elle présente de nombreux exemples de dommages réels ou potentiels.

ZUSAMMENFASSUNG
In diesem Beitrag werden Vorkommnisse im Baugrund behandelt, die eine oft nicht vorhersehbare Wirkung auf Bauwerke ausüben. Anhand von zahlreichen Beispielen aus der Praxis werden tatsächliche und mögliche Schadenfälle aufgezeigt.

1. INTRODUCTION

1.1 General

This paper was originally proposed by Working Commission I as an IABSE Survey on Soil-Structure Interaction. However there already exists a state of the art report on SSI published by the Institution of Structural Engineers in 1978 [1]. The report is now being revised and IABSE has been asked to participate in the preparation and publication of the revised report. It was therefore proposed that this paper should deal with the subject from a slightly different point of view, that is events in the ground which can affect structures in ways which may not always be foreseen.

Nature is one, but we can only think about it by breaking it up and dealing with the parts separately. Even when we can use a sophisticated conceptual model which links structure and foundation together, the analysis only deals with an approximation to the real situation and the real world can produce totally unforeseen effects outside the control of the engineer or of the owner. The history of the ground, in historic as well as geological time, is significant; construction activities affect other structures; ground water levels change. We assume that existing tendencies will continue, they may not.

Any change in physical circumstances in the vicinity of a structure can cause ground movements which affect the structure. The changes may occur during the working life of the structure, during its construction or even before it is constructed. The physical changes may be addition or reduction of loads on the ground, including excavation or filling, changes in ground water levels or flows, vibrations or temperature changes. Chemical effects are also possible. A local event not related to the structure may cause a widespread failure which affects the structure.

Ground movement in general is a four dimensional phenomenon; horizontal movements occur as well as vertical ones, even under purely vertical loading; movements also occur in time and take time to occur and the actual sequence and timing of operations can affect the magnitude and the direction of displacement.

Whenever loads are applied to or removed from the soil, movement occurs. The same applies to structures. Whenever ground is removed, movement occurs and affects nearby structures, especially those providing support to the ground but any nearby structure may be affected.

To take an example, a large excavation is made in clay. The sides are supported by sheet piles which are driven first and a strengthening framework is installed as excavation proceeds, creating the necessity and the opportunity for it. The walls move inwards, the amount depends on the properties of the soil, and of the supporting structure and the way in which it is installed. The bottom of the excavation heaves. A building near the excavation is affected by movement of the ground. The design of the building may or may not have taken the excavation into account. The design of the excavation must take the building into account, although it is not always obvious how far the effects will spread, especially if the new structure affects the existing flow of ground water.

It is necessary for the structural designer to be aware of problems which may affect the structure he is designing, and of problems which his works may cause to other structures.

1.2 Examples

The following pages contain examples of actual damage arising from largely unforeseen effects and some cases of potential damage which was avoided. They are all real cases, mostly from experience although a few come from the literature. They are not identified for good reasons. The categories in which they are grouped may serve as a partial checklist. They are:

- stiff structure on flexible ground
- changes in groundwater
- ground chemistry
- construction
- horizontal movements
- thermal effects
- ground cavities
- dynamic effects

Many of the examples which follow illustrate more than one point and would fit into several categories.

2. STIFF STRUCTURE ON FLEXIBLE GROUND

2.1 General

This is the most obvious case of soil structure interaction and gave rise to the earliest attempts at interactive analysis (beam on elastic foundation). Variable ground conditions with hard and soft spots under the same structure can cause difficulties. Variable conditions may be natural and they may also be artificially created, for example where changes of foundation level make it impossible to avoid over-excavation and subsequent refilling. An imposed loading which dramatically changes in intensity across the structure will be expected to give rise to extra complexity or problems. The following are examples of less obvious difficulties.

2.2 Examples

2.2.1 Inappropriate Analysis

In this example a fairly rigid structure was built on top of an embankment over soft ground. The Winkler spring analysis did not show the dished shape of settlement and the structure was not able to tolerate the actual movement.
This is a good example of an inadequate analysis method which did not model an important feature of the soil behaviour and consequently led to results which were quite misleading.

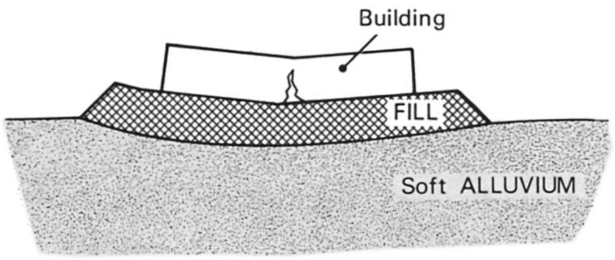

Fig. 1

2.2.2 Creeping Ground

Creeping ground on or near slopes may cause problems especially if part of a stiff structure is on creeping ground and the rest is not. An example of this was a multi-storey building founded on a raft. One end of the raft was over an area which was creeping due to a slip failure. The raft was unable to withstand the extreme differential movement and several large cracks opened in the structure, getting progressively wider towards the top of the building. Eventually a large part of the building was demolished.

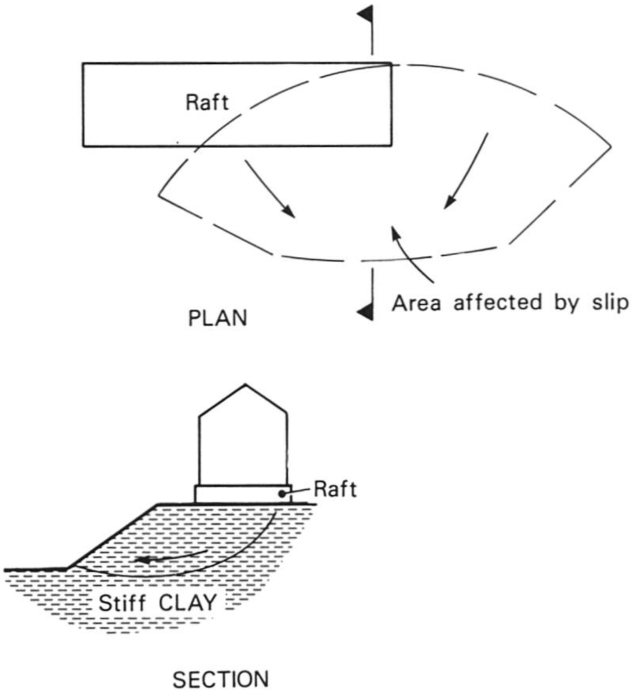

Fig. 2

2.2.3 Effects of Existing Structures

Where structures are founded on soft ground (natural or artificial) long term non uniform consolidation may occur. An extension was added to an existing structure on soft fill. As the soil under the existing structure had partly consolidated before the new extension was built, the soil consolidated more under the side of the extension away from the existing structure. This led to unacceptable cracking at the joint of the new and existing structures.

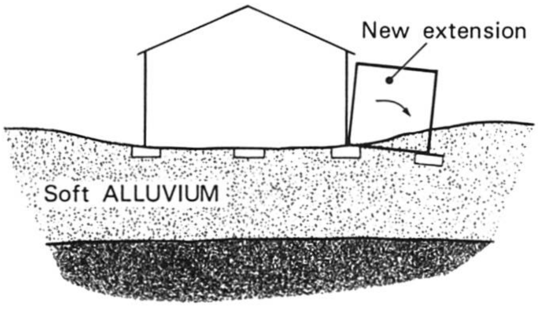

Fig. 3

2.2.4 Piled Structure in Soft Ground

Even where the structure is entirely carried on piles taken to firm underlying strata, problems can occur. If fill has recently been added to the soft material, the phenomenon of downdrag or negative skin friction will result, which overloads the piles. In addition, where the ground settles after the slab has been built, an unventilated cavity can form under the slab where gas can accumulate.

A very unusual example of problems arising from this situation occurred as follows.

A building was constructed on fill over soft clay. The structure, including the ground slab, was founded on piles taken to a firm stratum under the clay. Consolidation and settlement left a cavity under the floor. Outside the building the fill was taken to a level higher than the ground floor slab and eventually an extra metre of fill was added to make up for the consolidation and settlement. A bearing type slip circle failure occurred with heave into the hollow space, which damaged the floor slab, and horizontal ground movement which damaged the piles.

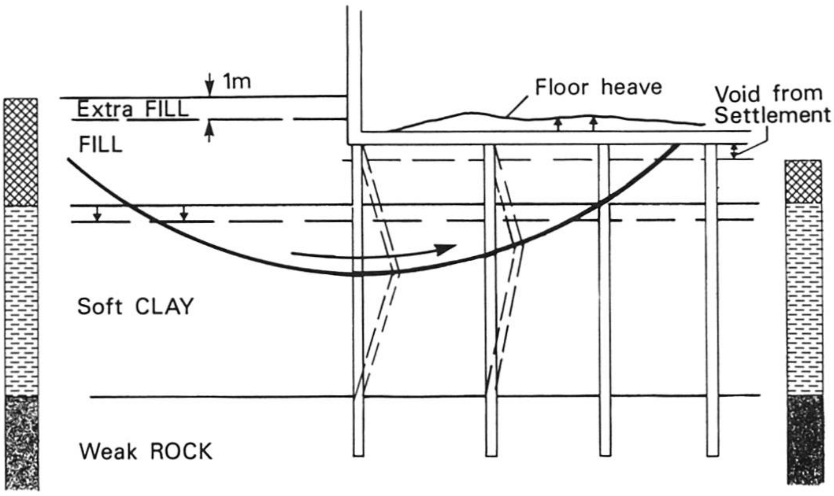

Fig. 4

3. CHANGES IN GROUNDWATER

3.1 General

Since water plays such an important role in ground behaviour, changes in the ground water regime can have substantial effects on structures. Some possible causes of changes in the water table are:

- leaking drains or water pipes,
- sinking of wells (or ceasing of extraction),
- dewatering or recharging on other construction sites,
- interruption of groundwater flow by other constructions,
- growth or removal of vegetation (especially trees),
- flooding.

Some possible consequences are:

- general movement from shrinkage or heave,
- increased or reduced water pressure on the structure,
- leakage because water level bypasses waterproofing,
- foundation failure or embankment failure affecting the structure,
- flotation.

When the structure itself plays an active role, some of the possible causes of change in the ground water regime are:-

- temporary drainage for construction,
- construction damage to existing drains,
- the permanent drainage for the building which can have long-term effects on its surroundings,
- the footings of the building forming drainage paths,
- interruption of the groundwater flow by basements or foundation walls,
- thermal effects (see Section 7).

3.2 Examples

3.2.1 General Extraction

During the 19th and early 20th centuries the increasing demand for water for industrial processes led to considerable lowering of the water table under London, Liverpool, Birmingham and many other old industrial cities in the UK and other countries. The nature of industry has changed in many of these cities and extraction of water has reduced considerably. The water table is rising and it can already be seen to cause problems of buoyancy, reduction of soil strength and flooding of basements.

The deep basement shown in figure 5 has a long design life and is in a city where the water table is rising. The load capacity of the piles under the basement would be reduced if the water level rises high enough. The pile bases have been made larger by under-reaming to deal with this eventuality.

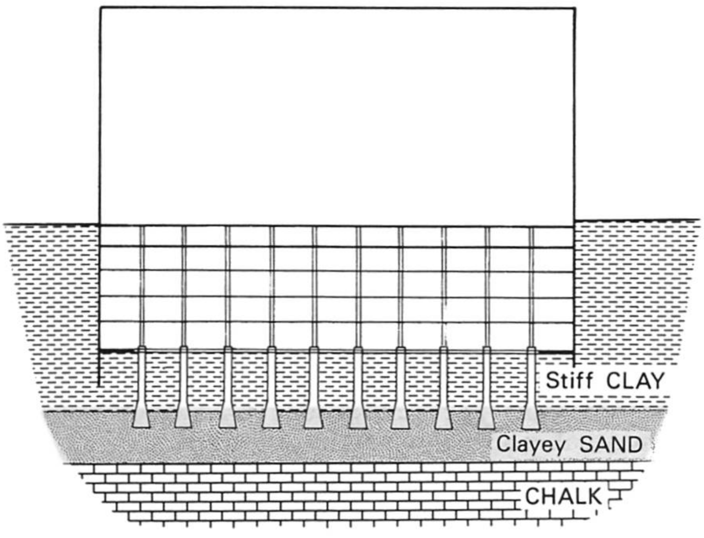

Fig. 5

3.2.2 Vegetation

Trees cause a local lowering of the water table which varies according to the season. The influence of single trees is beginning to be understood.

The effect of groups may however extend deeper and further as was shown by the example illustrated by figure 6. When buildings were placed in the area of the group of trees, which had been felled previously, they suffered severe distortion due to ground heave which lasted many years. In order to deal with this problem, it is necessary to gain a better understanding of the effects.

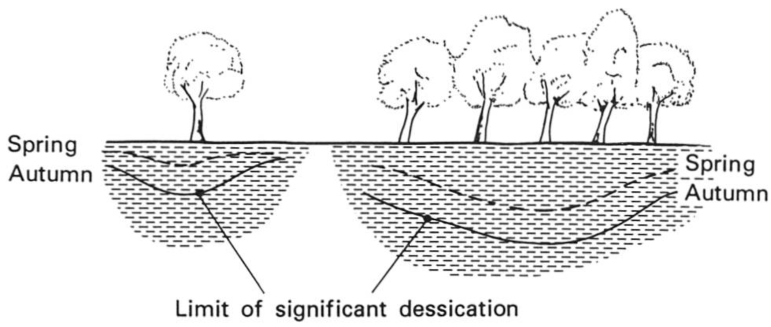

Fig. 6

3.2.3 Leaking pipes

A basement was constructed behind a contiguous pile wall constructed through 5m of gravel and the underlying clay. The wall was sealed to 1.5m above the ground water level observed before and during construction. A leaking water main caused a local rise in the water table and the basement was flooded; there was also some loss of ground with gravel flowing into the basement between the contiguous piles. If the wall had been completely sealed it might not have withstood the additional pressure.

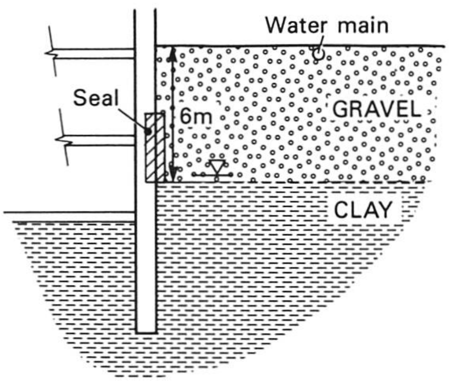

Fig. 7

3.2.4 Basements Modifying Groundwater Condition

Stations for underground railways have been constructed around the world using cut and cover techniques between diaphragm walls. This results in a long, narrow and deep basement. In the example shown in figure 8 the ground water flow across the station was obstructed, so that the level rose on the upstream side and fell on the downstream side. An older building some way downstream was founded on timber piles. Due to the basement construction the tops of the piles were now above groundwater level and rapidly decayed.

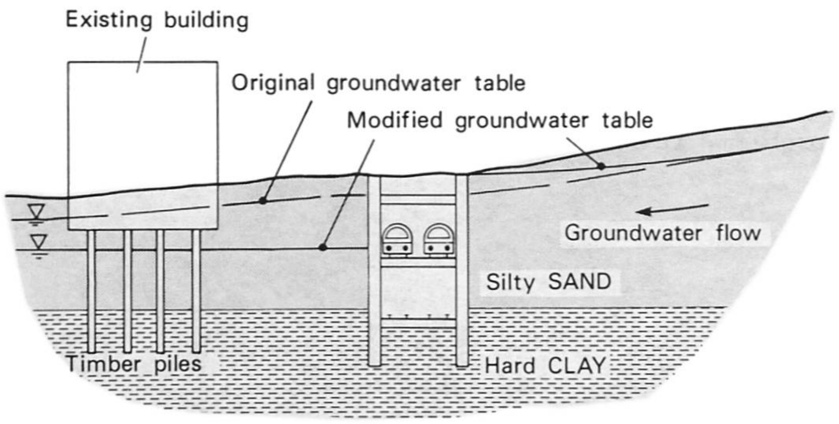

Fig. 8

3.2.5 Obstruction of Groundwater Flow by Deep Strip Footings

A building was underpinned by deep strip footings which obstructed the groundwater flow. This caused the water to rise above the level of waterproofing and caused dampness in the building.

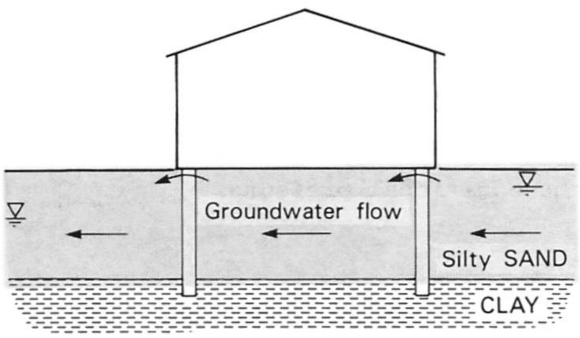

Fig. 9

3.2.6 Effects of Dewatering

During the construction of a similar station to that shown in example 3.2.4 the movements of the diaphragm walls were greater than expected. The ground between the two diaphragm walls was dewatered to allow excavation, causing a lowering of the water table outside the walls. This resulted in differential settlement and distress to masonry buildings close to the station (Fig.10). The effects were alleviated by recharging the groundwater outside the walls.

During the installation of diaphragm walls a tall building next to the station was observed to be settling in the opposite way to that expected; it was tilting away from the station (Fig.11). It was then found that the ground was being dewatered at another site, some distance from the far side of the building.

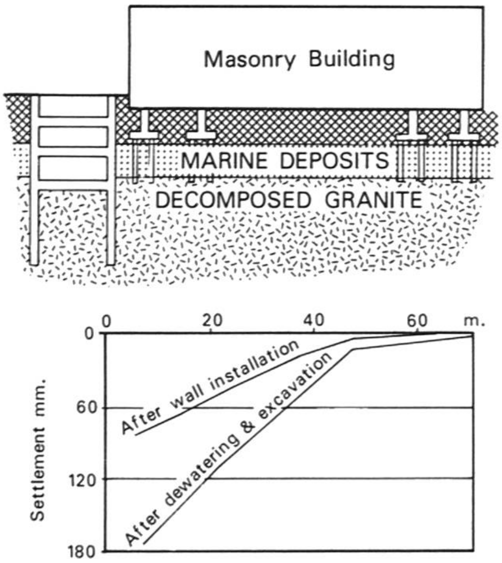

Fig. 10

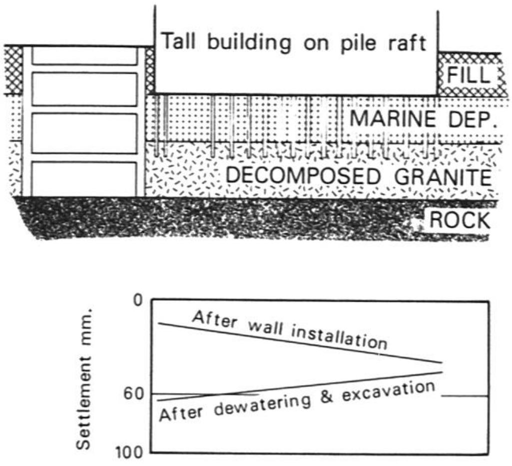

Fig. 11

3.2.7 Effect of Tunnelling

An underground railway station was constructed through decomposed granite using diaphragm walls penetrating into the intact rock below. A tunnel was subsequently constructed in the rock across the line of the station and below it. During construction, a fissure in the rock was encountered on the downstream side of the station. The level of the groundwater in the decomposed rock on that side dropped very rapidly, causing a large differential water pressure on the station.

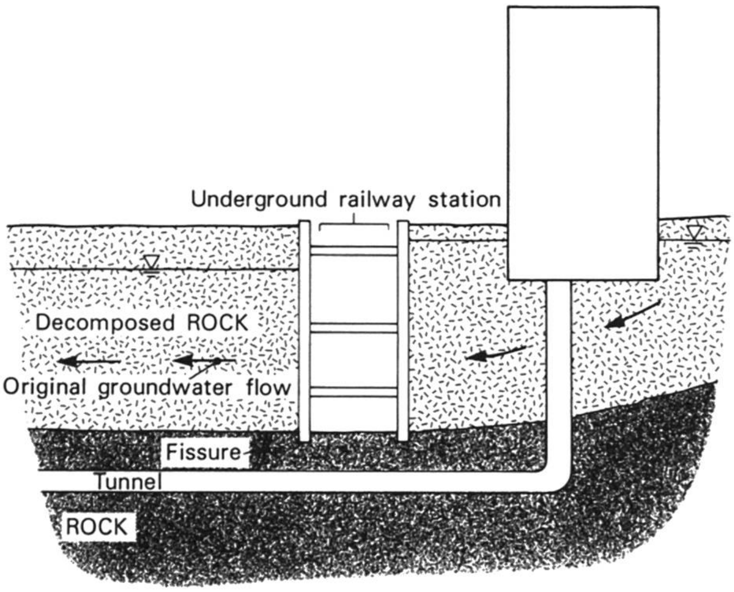

Fig. 12

3.2.8 Interruption of Existing Drains

During underpinning works for an ancient building, water level observations made over a period of 5 years, showed that the standing water level was about 1m below foundation level. A partly collapsed Roman drain was found along which water was still flowing. Some years after completion of the work the basement was flooded to a depth of 0.3m. A new building with a deep basement had been constructed about 500m away, slightly downhill of the ancient building. It is considered that this new construction severed a major Roman drain which led to the river and which had served to drain the city for 1800 years.

3.2.9 Groundwater Pollution

It is becoming more and more necessary to control the movement of groundwater to prevent the spread of pollution. A major road was to be taken in a cutting through existing refuse containing hazardous chemicals. It was necessary to construct cut-off walls to prevent pollution of drains. This required an understanding of the local groundwater regime so that water could be prevented from rising above the top level of the cut-off walls.

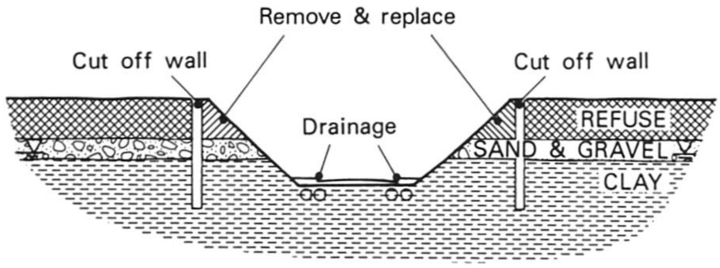

Fig. 13

3.2.10 Rate of Pore Pressure Dissipation

In order to reclaim land from a lake the developer placed a bund into the lake to form a closed body of water. He then proceeded to dewater the zone between the bund and the shore, intending to place and compact fill. After dewatering, the slope forming the original shoreline failed, as the pore pressure within had not had time to dissipate. The failure of the slope caused the destruction of a building.

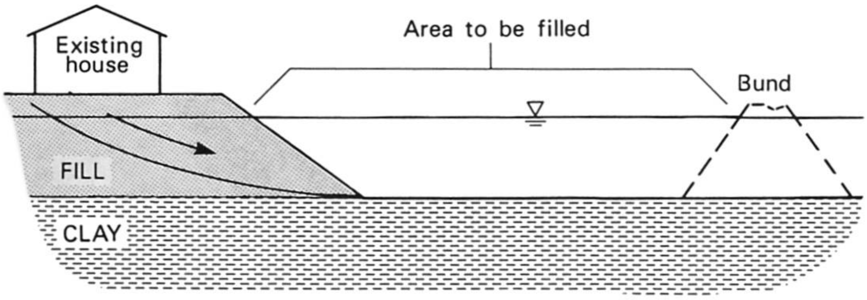

Fig. 14

3.2.11 Artesian Water Conditions

A cable-stayed roof had short anchor spans at each side of a very long span, resulting in uplift on the outer foundations. It was decided to hold them down with tension piles. The initial site investigation did not show the artesian pore pressure in the clay. Standpipes revealed the condition only after two months and the water in them continued to rise for some time. This affected the design of the tension piles.

4. GROUND CHEMISTRY

4.1 General

Foundations can be affected by the following:

- ground or water containing substances which attack concrete or steel
- organic material in the ground which decomposes causing settlement and/or buildup of gas
- loss of ground by solution in groundwater

4.2 Aggressive Chemicals

Aggressive chemicals may occur naturally or may be the result of industrial processes. In one example, a structure was to be founded in a soil with a pH of 3, because of its particular mineral content which resulted in sulphuric acid. The piles had to be constructed in pvc casings.
In another case some disused brick pits had been backfilled with chemical effluent containing a very high proportion of phosphorus. The water table had to be maintained at a high level to prevent spontaneous combustion of the material.

4.3 Organic Decay

Organic matter in the ground may be from vegetation, or waste timber. Buildings have even been founded on former cess pits. Where a structure is piled through soil containing organic material, continuing settlement of the material due to decomposition can occur, leading to downdrag (negative skin friction) on the piles.

4.4 Effect of Alkaline Effluent on Soil

A chemical plant, sited on clay, produced an alkaline effluent which leaked. This had the effect of dispersing the clay and making it readily erodable, resulting in large cavities which affected the foundations.

5. CONSTRUCTION

5.1 General

The method of construction, especially the timing, sequence and speed can have important effects on movement of the structure. Construction operations also affect neighbouring structures and sites, particularly the addition or removal of loads on the ground, removal of support and control or interruption of ground water (see also sections 3 and 6).

5.2 Examples Related to Sequence

5.2.1 Bridge Abutments

An abutment for the approach spans of a major highway bridge is a retaining wall founded on piles and retaining an embankment. The initial calculations indicated that the wall would rotate towards the bridge but, when the actual sequence of construction of the abutment, embankment and bridge deck was taken into account, the calculations showed that the wall would rotate in the opposite sense. The embankment construction procedure was modified and the backward rotation of the abutment was reduced.

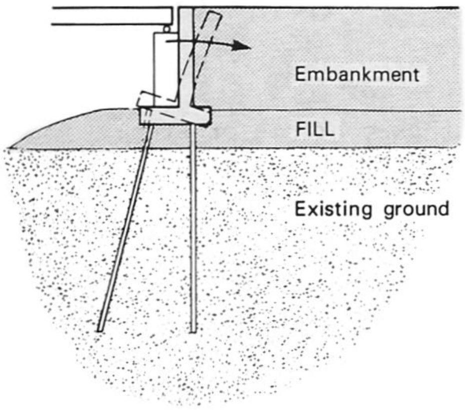

Fig. 15

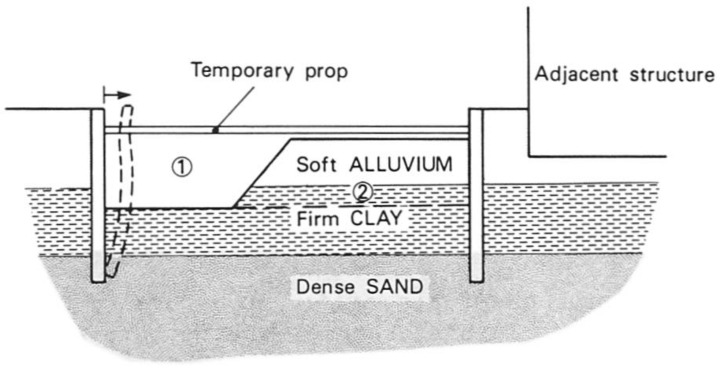

Fig. 16

5.2.2 Basements

Basement construction is another area in which the sequence of operations may be important. This example is of a basement which was being constructed between diaphragm walls with temporary props near the top of the wall. An existing building was sited close to one of the diaphragm walls. By excavating for the basement first on the side away from the building, the props were effectively stressed before the other side was excavated and the movement of the wall near to the building was reduced.

5.3 Examples Related to Method

5.3.1 Ground Anchors

Where it is not possible to provide temporary props, ground anchors are sometimes used to provide temporary support to walls. When the anchor is stressed, the anchored length moves and this can cause damage to nearby foundations. Damage can also be caused by changing loads on the anchors, as they are very elastic. In one case the use of an air flush to advance casing for anchors caused failure of several house foundations. This was believed to be due to a large increase in pore pressure in the soil over a wide area leading to a reduction in the effective stresses.

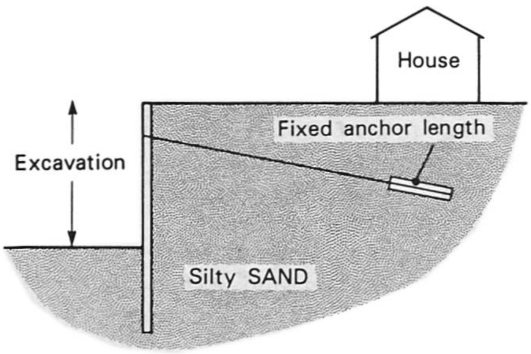

Fig. 17

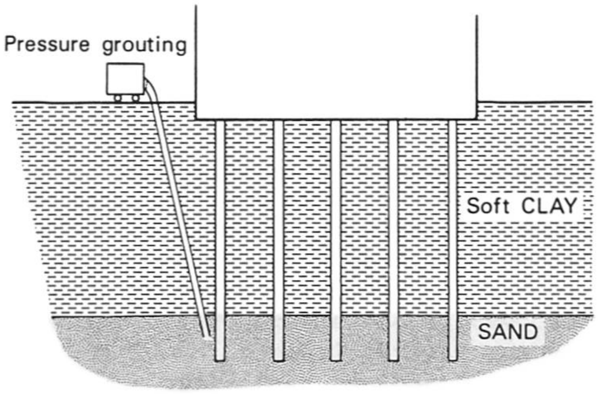

Fig. 18

5.3.2 Remedial Works

Remedial works can sometimes worsen damage. In this example, a building was supported on piles which were founded in sand underneath a layer of soft clay. Consolidation of the clay applied excess load to the piles through negative skin friction and the building was settling slowly. It was decided to use pressure grouting to increase the capacity of the piles in the sand. The pressure of the grouting caused a significant increase in pore water pressure within the sand, leading to failure of the piles.

5.3.3 Settlement of Temporary Works

Many bridge sites in river valleys have a thick layer of soft material overlying the founding stratum. Where a post tensioned concrete bridge deck is constructed on falsework which is supported directly on the ground, there will generally be differential settlement between the falsework and the permanent foundation, after concreting the deck which has to be added to the compression of the falsework itself. The effect of this could be much worse than it would be for a reinforced concrete deck, because post tensioned decks normally do not contain enough passive reinforcement to prevent cracking of the concrete after it sets and the active reinforcement is not effective until it is stressed. Therefore the decks could be damaged before post tensioning is carried out. For the bridge in this example it would have been very expensive to provide piled foundations for the falsework and the design of the falsework made it difficult to jack to counteract settlement. However by applying some of the prestress very early it was possible to avoid damage.

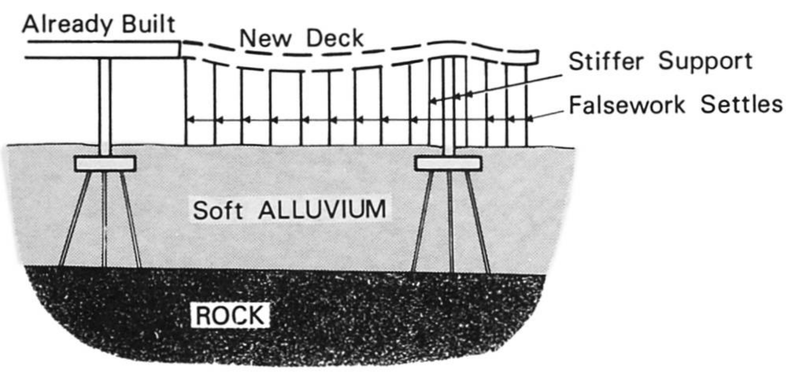

Fig. 19

5.4 Examples Related to Control of Water

5.4.1 Inadequate Dewatering

When excavations are taken below the groundwater table it is vital that adequate means of dewatering are installed at all stages of construction. Dewatering the surface of the excavation by pumps and sumps is frequently inadequate especially in fine sandy or silty materials. In the example illustrated in figure 20 the pore pressure at A almost matched the overburden pressure and consequently the effective stresses were almost zero. Soft spots were observed in the base of the excavation and extra digging was carried out to get to good ground. This only aggravated the situation and eventually two mechanical excavators were lost as they sank below the surface of the excavation.

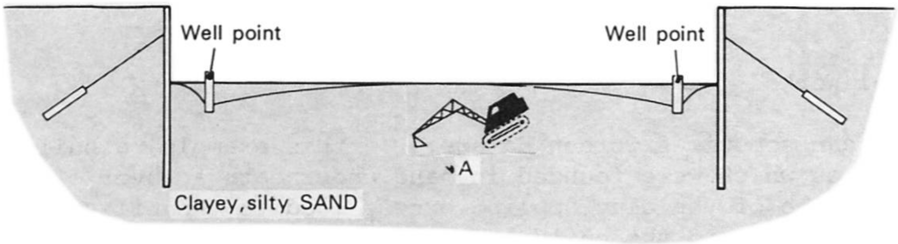

Fig. 20

5.4.2 Buoyancy During Construction

Some large tanks were being constructed in ground subject to flooding. To protect the tanks from flotation, when empty, each one was surrounded with free draining material and a safety valve was provided in the floor. While the tank was being built the valve was blocked with paper to prevent concrete from entering it. A flood occurred during construction, water entered the free draining material, and the tanks floated out of the ground.

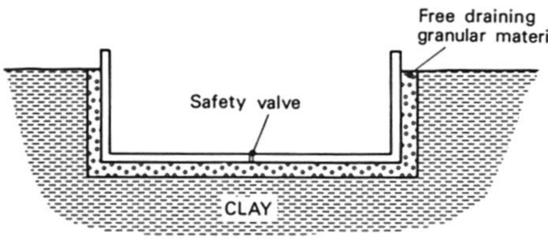

Fig. 21

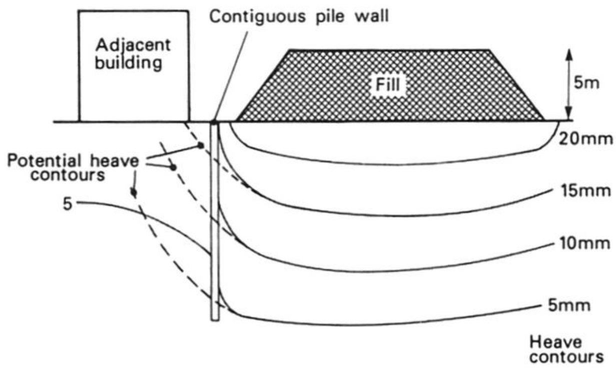

Fig. 22

5.5 Examples of Effects of Construction Operations on Surroundings

5.5.1 Removal of Load

An existing building was sited close to a 5m high spoil heap. The spoil heap was to be removed which would cause differential heave, affecting the building. To protect the building a contiguous pile wall was constructed between it and the heap. The effect of this was to increase the overall heave under the building, but to reduce the differential heave.

5.5.2 Flexible Retaining Wall in Soft Clay

Where ground is excavated behind, or within, flexible retaining walls such as sheet pile walls, movements take place. For walls in the practical range there are plots available of maximum movement expected. In soft clays the movements become large, especially at depth (see figure 23). The maximum depth of excavation in soft clay is limited by the strength of the clay and is virtually unaffected by the penetration of the retaining wall. This is because a bearing capacity failure of the clay at the base of the retaining wall will be mobilised.

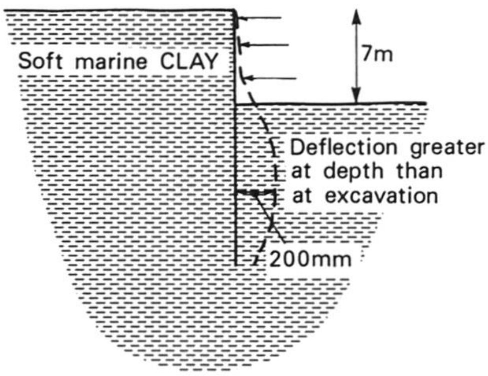

Fig. 23

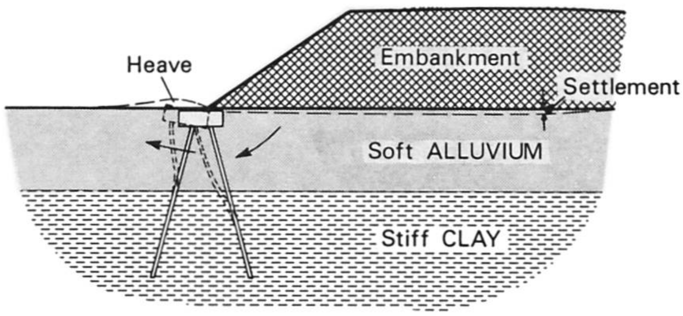

Fig. 24

6. HORIZONTAL MOVEMENTS

6.1 General

In general, vertical movements of the ground are accompanied by horizontal movements which can be more damaging to structures than the vertical ones. The waves of tensile and compressive ground strain caused by long wall mining and the horizontal ground movements during earthquakes are well known examples, but there are many more common circumstances in which horizontal movements have important effects.

6.2 Examples

6.2.1 Embankments

Heavy vertical loads cause horizontal movements in the ground. Where embankments are founded on soft ground, existing buildings near the toe of the embankment can be damaged. The piles supporting a foundation for a bridge abutment were constructed before the embankment was placed and were damaged by horizontal movements which occurred when it was placed. It is necessary to consider the construction sequence of embankments and piles carefully if such damage is to be avoided. (See also 5.2.1).

6.2.2 Driven Piles

The displacement of ground caused by driving piles causes lateral movements. Piles previously driven through 10m of soft becoming stiff silty clay were displaced as much as 60mm by driving of subsequent ones.

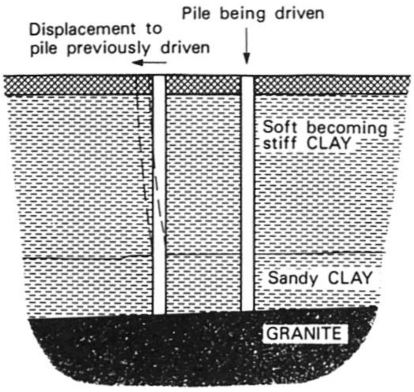

Fig. 25

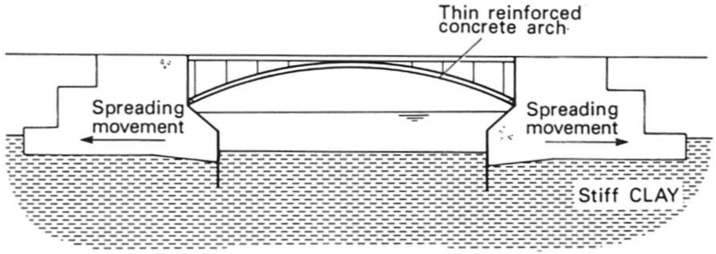

Fig. 26

6.3 Integrity of Horizontal Support

Horizontal support from the ground is essential to carrying vertical loads in the cases of structures such as untied arches and portal frames or earth anchored cable supported structures as well as gravity retaining walls. It is necessary to ensure that subsequent works do not remove that support. Flexible buried structures, such as steel culverts, are particularly sensitive to removal of ground around them.

6.4 Examples

6.4.1 Arch Bridge

A highway bridge over a river had a concrete deck supported by a reinforced concrete arch slab thrusting against cellular abutments founded in stiff clay. The arch was designed to tolerate spreading of the abutments due to movement of the clay. Twenty years later another bridge was to be constructed alongside. If the new bridge had been built as an arch it would have caused further horizontal movement in the clay and the arch of the first bridge would have been damaged. A different structural principle was used. (There are, many old masonry arch bridges founded in clay, but masonry arches are effectively very flexible).

6.4.2 Tunnel Crown

A section of railway ran in a shallow tunnel constructed through Coal Measures and clay by cut and cover. The tunnel roof was an arch of reinforced concrete supported directly on rock or on mass concrete walls depending on the local ground conditions. A new highway was to be built near the railway and precautions had to be taken to avoid removing horizontal restraint from the tunnel roof.

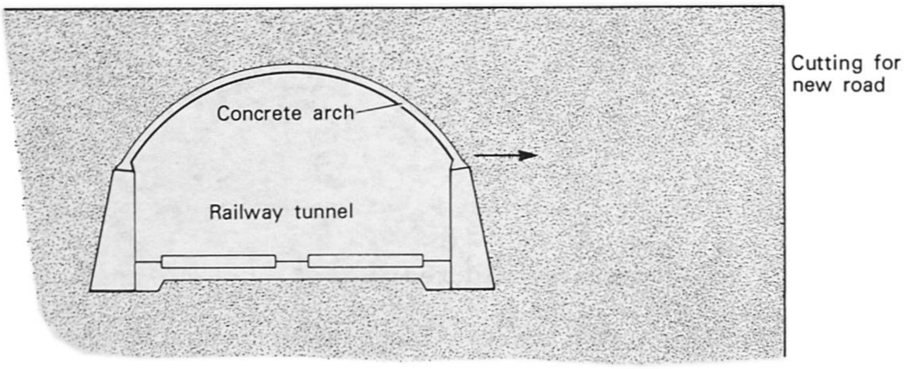

Fig. 27

6.4.3 Compaction of Backfill

A gravity wall about 5m high retained dry sand on which a building was founded. A sewer was installed in front of the toe of the wall in a trench about 2m deep. The sewer was correctly installed in short lengths of trench but the backfill was poorly compacted, which led to a bearing capacity failure under the toe of the retaining wall, badly damaging the building.

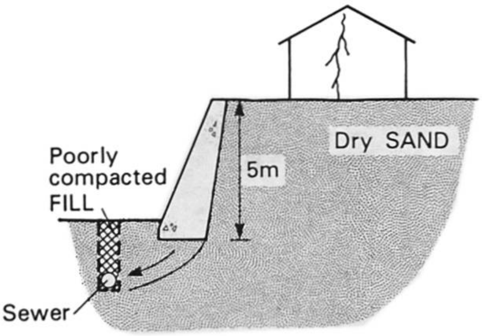

Fig. 28

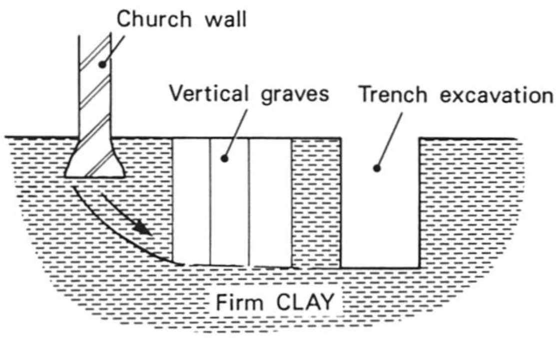

Fig. 29

6.4.4 Combination of Known and Unknown Excavations

A trench was excavated near a church. There were vertical graves in the ground which were not allowed for in design because they were not known about. They combined with the trench excavation to provide a path for a slip and the church was demolished.

6.4.5 Flexible Buried Petrol Tanks

Flexible steel or fibreglass tanks are frequently used at petrol stations. To install an additional tank it can be seen that extra support must be given to the existing tank if it is to be able to function during the installation.

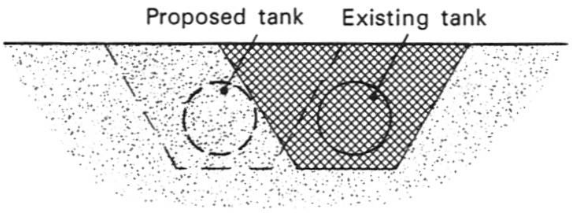

Fig. 30

7. THERMAL EFFECTS

7.1 General

Two different kinds of effects are considered:

- thermal movement of the structure causing interaction with the ground
- thermal effects which cause changes in the moisture content of the ground

7.2 Thermal Movement of Structure

Many buildings are partly protected from external temperature changes and the effects of solar radiation. Bridges, which are not protected, are generally designed to allow for changes of length with temperature and are isolated from the ground at one or both ends to allow for this. In European practice this applies to the decks of all except very short bridges (say up to 10m long or occasionally more). In the United States of America bridges up to 240m long have been built on flexible end supports in contact with the ground, apparently without ill effects [2], [3].

7.2.1 Example of Differential Expansion Due to Heating Plant

In a deep basement it was discovered that the temperature changes induced by a heating plant were causing the basement propping forces to be significantly affected. This must be a common phenomenon which is not normally taken into account in design but the authors are not aware of any examples of problems arising caused by it.

7.3 Thermal Effects on Ground

The temperature of a structure in use affects the ground under and around it as in the following examples. In both of these, it is the recovery from the original thermal effect which has caused the recent problems.

7.4 Examples

7.4.1 Cold Store

Under cold stores lenses of ice form in the ground and grow by migration of moisture from the surrounding ground. When cooling ceases and the lenses thaw, the ground is supersaturated causing high pore water pressures and greatly reduced strengths.

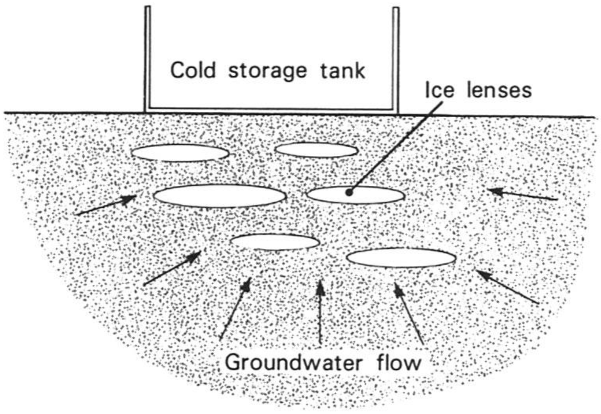

Fig. 31

7.4.2 Brick Kiln

A brick kiln about 60m x 30m in plan was sited on 3m of brick rubble on clay. The kiln was removed. A new structure built there suffered 500mm of relative movement. Investigations revealed that the clay had been affected by heat to a depth of at least 20m. The migration of water back into the clay took place over many years.

8. GROUND CAVITIES

Cavities in the ground can be natural, due to solution of minerals in water, or artificial, caused by mining or by effluent leakage. Natural solution cavities are frequently found in limestone and chalk. Generally in chalk these are filled with loose or soft soil and referred to as sinkholes. In limestone the cavities can vary from small infilled cavities to large open caverns.

A Middle Eastern island is used for storage and processing of oil. Cavities were continually being discovered near foundations after heavy rains. These were found to be associated with gypsum rich rocks.
A case where clay was affected by alkaline effluent making it easily erodable has been referred to in 4.4.

Damage due to collapse of old mine workings or from settlements caused by current mining is not unexpected and consequently is not discussed here.

9. DYNAMIC EFFECTS

9.1 General

Earthquakes and other dynamic effects give rise to a host of complexities which are beyond the scope of this paper. There are several instances however, when the soil behaviour can lead to very damaging effects and these are mentioned below.

9.2 Pore Pressure Rise

The phenomenon of liquefaction, the state where the pore pressure in the soil increases during the excitation to such an extent the soil appears to behave as a fluid, is well known. It must be remembered that there may be a significant rise in the pore pressure without liquefaction occurring and the effects of the rise may lead to failure and should be assessed. Excess pore pressure rise dissipating from a stratum susceptible to pore pressures after an earthquake has caused failures in adjacent strata, sometimes several days after an earthquake. A similar effect has been observed during compaction of fine grained soils. If the excess pore pressure induced by the compaction is not able to dissipate rapidly, further compaction may not only be of no benefit but may be detrimental.

9.3 Stronger Soil than Expected

At sites where there is a weak layer at depth it is recognised that failure of the weak layer will prevent large accelerations from reaching the surface. It has not always been recognised that if the soil is stronger than assessed then larger accelerations can be transmitted. Care must be taken to ensure that site investigation disturbance effects are allowed for when assessing maximum soil strength.

9.4 Site Resonance

Sites with thick layers of soft or loose soil are likely to resonate at a particular frequency during an earthquake. The ground surface motion will therefore contain significant energy at the resonance frequency and if there are any structures with a similar resonance frequency disastrous consequences may result. The 1985 earthquake in Mexico City produced many graphic examples of this effect.

9.5 Dynamic Compaction

Vibrating machinery has been known to cause compaction of soil under its foundations, leading to excessive settlement.

9.6 Fluidisation

Fluidisation, a different phenomenon from liquefaction, is caused by the movement of a fluid through the pores of a granular material.

A recent paper [4] suggests that the catastrophic failure of a bridge in the Middle East was due to a pressure wave in the ground which ran ahead of the flood wave coming down a wadi. The piers were observed to move before the flood reached them.

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