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G. Hannink

Delft Geotechnics, The Netherlands

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Reconstruction of the Settlement History of Buildings

G. Hannink
Project-engineer, Delft Geotechnics, Delft, The Netherlands

SYNOPSIS: Although it is a well-known fact that buildings can settle, it is often not known how much settlement has occurred since the construction. Three case studies in the Netherlands are presented which deal with the following questions: has the settlement process stopped or is it continuing and if so, what settlements can still be expected in the future? All three cases show large settlements of up to a maximum of 0.8 m since construction. This paper shows how the magnitude of the settlement since the construction can be reconstructed by analysing settlement data, covering only a relatively short period of time.

INTRODUCTION

The fact that a building is settling is often only recognizable after damage to the walls becomes visible or other harmful effects have been discovered. Questions then arise about the future of the building, and usually only then is a measuring program initiated. The amount of settlement which has occurred since construction is normally not known. Nonetheless the measuring program is required to lead, as soon as possible, to an answer to the question: what is the present rate of settlement? Extrapolation of this measured rate usually makes it possible to predict the settlements to be expected in the future.

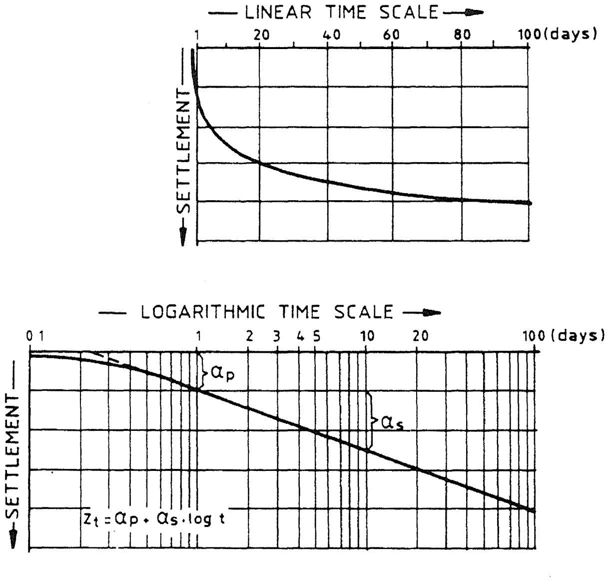

Fig. 1 Settlement according to Keverling Buisman, shown at linear and logarithmic time scales

SETTLEMENT THEORY

The settlement of a building is related to the properties of the subsoil. In 1938 Keverling Buisman presented the following settlement formula which takes into account secular effects, Figure 1; the formula is based on a study of time-settlement diagrams of both structures and laboratory samples.

$$z_t = \sum^{\text{all layers}} d(\alpha_p + \alpha_s . \log t) . \Delta p \qquad (1)$$

where: z_t = total settlement of the soil layers considered, at time t
d = thickness of the particular soil layer
α_p = settlement property of this soil layer, representing the direct effect
α_s = settlement property of this soil layer, representing the secular effect
t = time
Δp = load increment on the particular soil layer (the moment of application of the load is taken as time = 1)

Keverling Buisman states that the settlement process only agrees with this formula, if the excess pore-water pressure in the respective soil layers dissipates in a short period like in a laboratory test. In reality, because of the thickness of the soil layers, this will not be the case, and the increase of the effective stress and therefore the settlement process will be delayed. In practice an increase in load on the subsoil will also take place in a certain period of time. Keverling Buisman therefore introduced the term "equivalent exterior loading time" meaning that (imaginary) point of time when, in the long term, an exterior load, suddenly applied, would lead to a settlement process identical to that which occurs when an exterior load is applied gradually, for example a sand fill.

Keverling Buisman sees the gradual increase of the (internal) effective stress, due to the decrease of the excess pore-water pressures during the hydrodynamic period, as if it were the result of a comparable external increase of the load. An "equivalent internal loading time" can now be introduced as a zero value for the time in the logarithmic settlement process in a similar way as for the external load. The equivalent internal loading time occurs later than the equivalent external loading time. In an analysis of settlement behaviour, it will make little difference if the point of time to be considered is taken with regard to the start of loading or with regard to the equivalent internal loading time, as long as the point of time to be considered occurs a long time after the equivalent internal loading time. The settlement formula proposed by Keverling Buisman was used in the three following case studies.

CASE STUDY I: KAMPEN

Hanze is a post-war extension of the city of Kampen built in the surrounding polder. The site was raised with several metres of sand in 1949 before the construction of houses. The majority of the buildings are two and three storey low-rise blocks of flats founded on continuous footings. Some blocks have raft foundations. Many of the original 30 blocks were built on filled-in ditches in the period 1952-1957. The majority of these blocks show differential settlements and cracks in the brickwork. For this reason one of the blocks was pulled down in 1962. The following soil layers occur:

- the sand fill which was used for raising the site the thickness of which varies between 3 and 6 m;
- compressible layers, consisting of mainly peat and with some clay, the thickness of which varies between 1 and 4 m
- a pleistocene sand layer; the level of the top of this layer varies between 1 and 7 m below New Amsterdam Level.

The ground surface is at present about 3 m above New Amsterdam Level. The sand fill and the sand layer show different pore-water pressures. There have been no major changes in the groundwater regime since the construction of the houses.

Building deformation

Levels of four flat blocks have been taken over a long period; one of these blocks was pulled down in 1962. The measurements of this particular block were started in 1957. In this period 11 sets of measurements were made. Measurements of the other three blocks started in 1961 and, in the period 1961-1983, 19 sets of measurements were made. The measurements show a continuing settlement process. The magnitude of the settlements in the period 1961-1983 varied between 0.05 and 0.14 m. Soil investigations have shown that, by raising the site with the sand fill, the original thickness of the compressible layers was reduced by 30 to 40%. This means, depending on the magnitude of the original thickness of the compressible layers, a settlement of the compressible layers of 0.5 to 3 m. The largest part of this settlement took place before the flats were constructed.

Settlement analysis

The available data indicate that the continuing settlement process, and the related increase in the differential settlements in each block of flats, was mainly caused by the continuing settlement of compressible layers due to raising the level of the site before construction. The settlements of the block which was pulled down and the other three blocks were checked to see if they varied logarithmically with time. It was assumed in this investigation that the hydrodynamic period ended before the measuring period and, therefore, that a secular settlement process took place according to the formula of Keverling Buisman. The following formula was used for the analysis:

$$l(t) = a - b \log t/t_o \qquad (2)$$

where: $l(t)$ = level of the reference point at time t (m to New Amsterdam Level)
a = constant (m to New Amsterdam Level)
b = constant (m)
t_o = unit of time (1 year)
t^o = time of measurement in years after t_1
t_1 = equivalent internal loading time

The equivalent point of time of the application of the external load could be determined rather accurately from the available data, but the equivalent internal time of loading, due to the hydrodynamic period of the compressible layers, occurs some time later and is much more difficult to determine. The relationship between the level of the reference point and the time, that is, the determination of the constants a, b and t_1, was therefore investigated for a number of different points of time t_1. Figure 2 gives the results of the regression analysis for one measuring point. The results of the calculations show a good to very good relationship between the level of the reference point and the logarithm of the time. The equivalent internal loading time has been determined as 1st January 1953 for two blocks of flats and as 1st January 1954 for the other two.

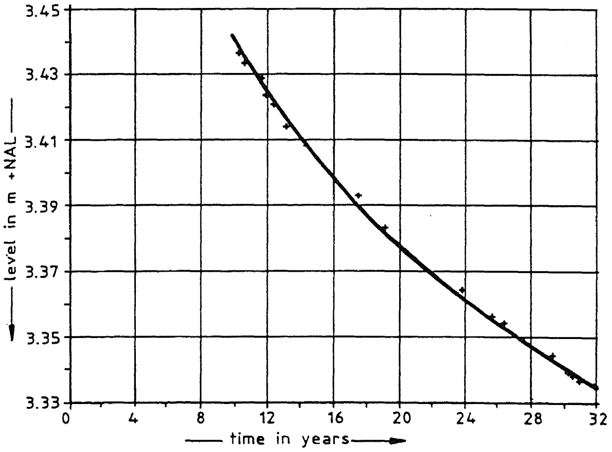

Fig. 2 Time-Settlement behaviour of a measuring point

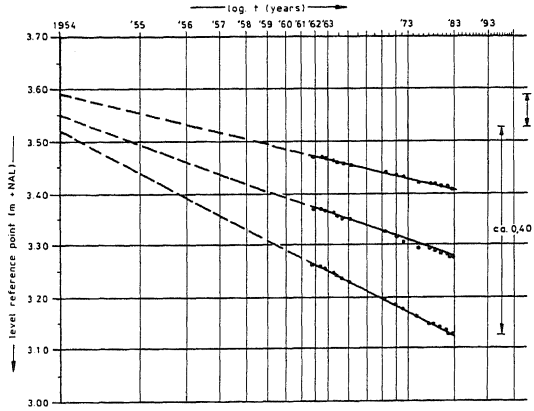

Fig. 3 Determination of the absolute settlement since construction

Because the four blocks were built around 1953/1954, the absolute settlement of each measuring point since construction can be derived directly from the calculated level of the reference points on 1st January 1953 or 1954, Figure 3. The settlement for the three remaining blocks of flats, is about 0.4 m maximum. The constant a in the Keverling Buisman formula which is the calculated level of the reference point in metres relative to New Amsterdam Level on 1st January 1953, should be the same for each block, because the reference points have been placed in the same bed joint. In fact, however, there are differences of up to 70 mm, Figure 3. An accurate prediction of future settlements has been made, based on the reconstruction of the settlement process. Extrapolation of the present logarithmic with time settlement process indicated future settlements which vary between 1 and 3 mm/year. The analysis shows the load on the compressible subsoil as if recorded in a long duration settlement test which satisfies the formula of Keverling Buisman. The measured settlement of the buildings serves as an accurate indication of the settlement process of the subsoil. Such long duration tests are not practicable in the laboratory. It is therefore striking that an empirical formula, introduced about 50 years ago and mainly based on short duration laboratory tests, can describe the settlement process of the houses in Hanze, which has been going on for more than 30 years, so accurately.

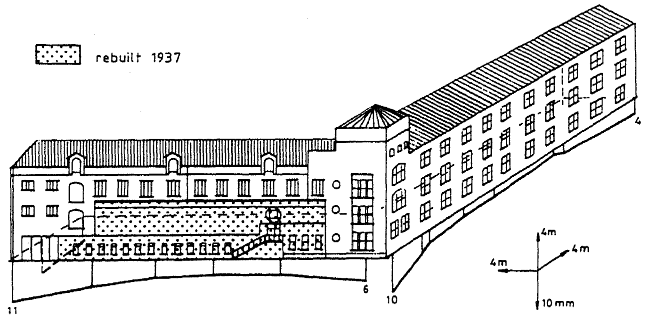

Fig. 4 Settlements in the period December 1980 to January 1983

CASE STUDY II: VLAARDINGEN

The ROMI factory was originally a sugar refinery which was built on a site outside the dikes of the New Meuse at Vlaardingen. The level of the site was raised shortly before construction. The oldest part of the building dates from 1898. One wing of the building was extended after 1900, the other after 1909; the factory was partially rebuilt in 1937. The building is founded on tapered timber piles about 20 m in length and with a diameter at the top of 280 mm. The brickwork of the building is seriously cracked. The following soil layers occur:

- the sand fill which was used for raising the site the thickness of which varies between 4 and 5 m;
- compressible layers, mainly consisting of clay and peat, with a thickness of about 17 m;
- a pleistocene sand layer in which the piles have been founded; the level of the top of this layer is about 19 m below New Amsterdam Level.

The ground surface is at present about 3 m above New Amsterdam Level. The phreatic groundwater level is about New Amsterdam Level. The piezometric level of the groundwater in the sand layer below the compressible layers is 2 to 3 m below New Amsterdam Level.

Building deformation

Levels of reference points fixed on the outside walls have been taken in the period December 1980 to January 1983. The measured, total, settlements varied between 1 and 11 mm in 25 months, Figure 4. During the rebuilding in 1937 the lower part of the north-west front was replaced, the upper part being maintained. Levels were taken of the top of a decorative "header" course of bricks laid in the brickwork walls constructed in the period 1898-1909. Levels were also taken of a bed joint laid above the part that was renewed in 1937, Figure 5. It is assumed that the bed joint and the header course were horizontal at the time of construction, and that the extensions of 1900 and 1909 were connected, as far as the level of the brickwork is concerned, to the existing building. Measurements will therefore give a clear picture of the differential settlements since the construction: the maximum settlement, up to 1982, was about 575 mm.

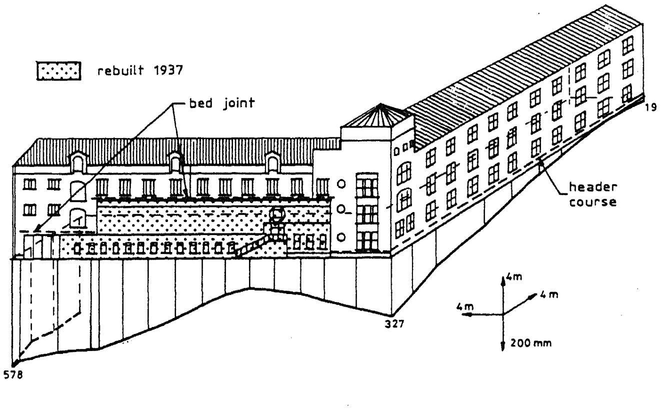

Fig. 5 Differential settlements in the walls constructed in the period 1898-1909

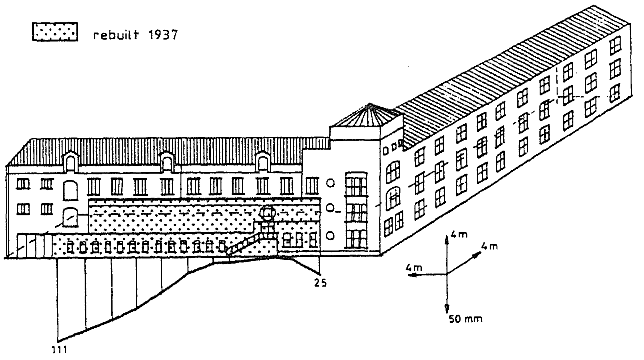

Fig. 6 Differential settlements of the wall rebuilt in 1937

Levels were also taken of the part of the building renewed in 1937, Figure 6. The maximum differential settlement in the period 1937-1982 was about 110 mm.

Settlement analysis

The measured differential settlements of the building are very large for a foundation on piles. The settlement behaviour is, in fact, more like that of a spread foundation. It is sometimes possible to relate the settlement of piles due to negative skin friction to the settlement of the surrounding soil (Hannink and Talsma, 1984). The formula of Keverling Buisman has, therefore, also been used to analyse this case. First the rate of settlement in the period 1980-1983 was determined for each measuring point as accurately as possible. The assumption that settlement is linear with time is reasonable here. The rate of settlement varies between 1 and 5 mm/year. Because only differential settlements were known, it was also necessary to assume here that the lines which represent the settlement process, for each measuring point, according to the formula of Keverling Buisman, intersect each other at the zero of the absolute settlement, Figure 7. The figure shows, for each measuring point, the same ratio between the absolute settlement since the construction and the present rate of settlement Figure 8 shows, for each measuring point on the walls constructed in 1898-1909, the rate of settlement in the period 1980-1983 (x-axis) and the differential settlement since the construction up to 1982 (y-axis). The result is a rectilinear relationship. At x = 0 the y-value can be read from this relationship which should be added to the differential settlement for each measuring point in question to obtain the absolute settlement since the construction up to 1982. The results show that this value amounts to between 24 and 68 mm depending on the number of measuring points accepted, Figure 8. The same approach has been used for the part renewed in 1937. The results show that, depending on whether three or four measuring points are considered, 83 or 98 mm should be added to the differential settlement to get the real settlement in the period 1937-1982, Figure 9.

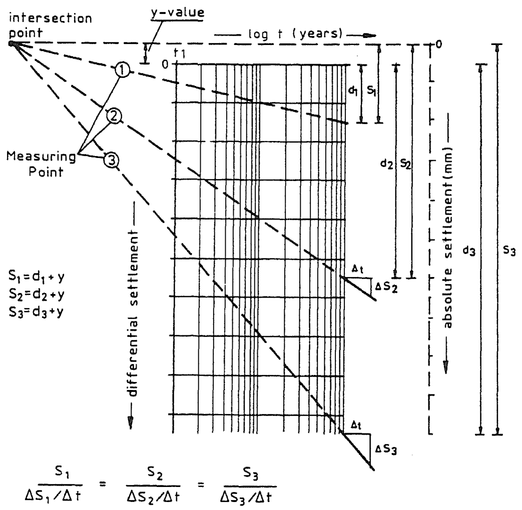

Fig. 7 Assumption for the settlement process

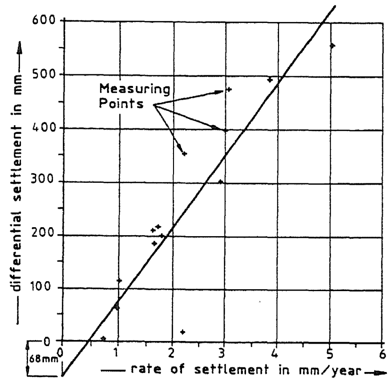

Fig. 8 Relationship between the rate of settlement and the differential settlement in the period 1898-1982

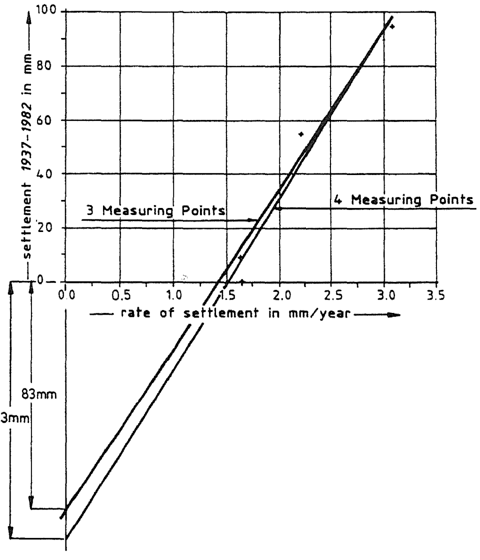

Fig. 9 Relationship between the rate of settlement and the differential settlement in the period 1937-1982

Because of the assumptions which were necessary, the ratio between the absolute settlements since the construction up to 1982, and the settlements in the period 1937-1982 for the part of the building renewed in 1937, was checked for each measuring point to determine whether or not it was the same everywhere, Figure 10. This ratio is indeed everywhere the same and because the line determined by regression analysis should go through the intersection of the axeses, leads even to more accurate results. The minimum settlement of the building, in the period since the construction up to 1982, amounts, according to the calculations, to 68 mm, and the maximum settlement to about 650 mm, Figure 11. In the period 1937-1982 the minimum settlement of the renewed wall was 83 mm, and the maximum settlement about 190 mm. Further analysis showed that the part renewed in 1937 since 1937 has settled almost linear with time and not, according to Keverling Buisman, logarithmically with time. Tracing the cause of this discrepancy was beyond the scope of the investigations. Possible causes are a change of load on the foundation piles in 1937, effects of drainage of the pleistocene sand layer and creep of the timber piles. However, the same ratios presented in Figure 7 also apply when the settlement process is linear with time, and the results of the calculations will therefore not change. A continuation of the settlement process, measured in the period 1980-1983, can, for the larger part of the building, be expected in the near future with a rather large amount of certainty. Settlements which vary between 1 and 5 mm/year must be reckoned with.

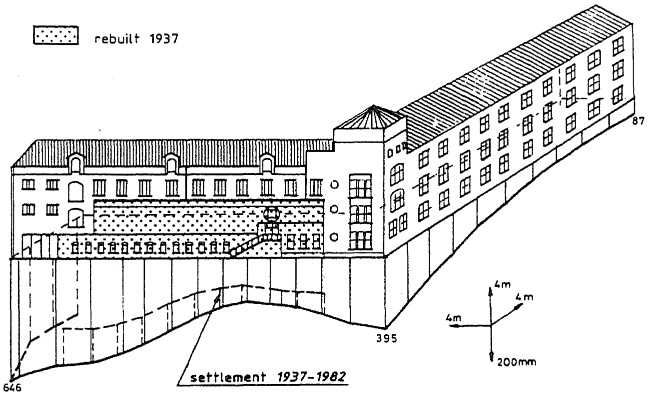

Fig. 11 Calculated absolute settlements up to 1982

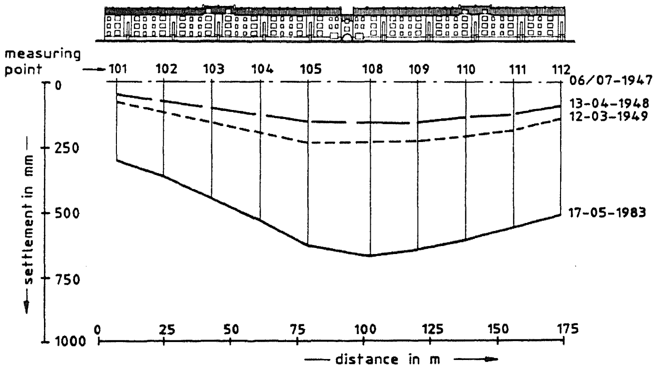

Fig. 12 Settlement of the front side since construction

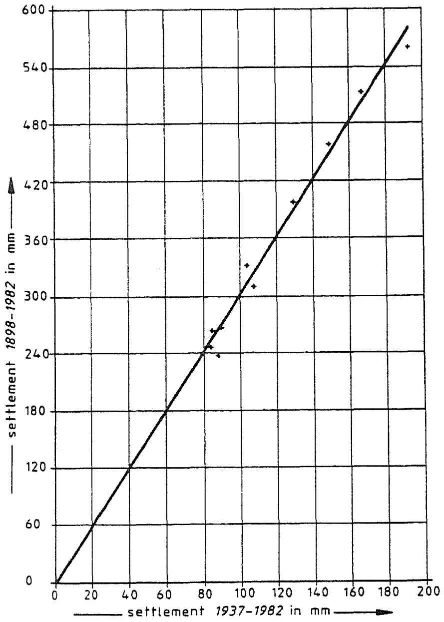

Fig. 10 The absolute settlement in the periods 1898-1982 and 1937-1982 for the part of the building renewed in 1937

CASE STUDY III: DELFT

The flat block in the De Colignystraat was built in 1946/1947 and is founded on raft foundations. The flat block is a three, locally four storey building and contains 58 flats. The flat block is divided into two by a gate, and has a basement floor which is partly below ground level, Figure 12. The basement floor does not continue under the gate. The ground level was raised by 0.7 to 1.0 m of sand at both sides of the building during the construction. The building brickwork is seriously cracked near the gate. The following soil layers occur below the building:

- compressible layers down to about 10 m below New Amsterdam Level, consisting of clay, sandy clay and peat; a sand layer was encountered, however, between about 3 and 6 m below New Amsterdam Level at the southern part of the building;
- sandy clay and clayey sand between 10 and 14 m below New Amsterdam Level;
- compressible layers between 14 and 17 m below New Amsterdam Level;
- a pleistocene sand layer below 17 m below New Amsterdam Level.

The groundlevel at present is about 2 m below New Amsterdam Level.

Building deformation

Since construction, levels of the building have been taken in 1947, 1948, 1949 and 1952. A new measuring program was started in 1982. This case differs from the preceeding cases because the zero-situation is known, and the following absolute settlements of the building were observed for the period 1947-1983, Figure 12:

- south end (front): 300 mm
- middle (front): 650 mm
- middle (back) : 800 mm
- north end (front): 510 mm

The following settlements were measured in the period 1982-1984, Figure 13:

- south end (front): 3 mm
- middle (front): 8 mm
- north end (front): 5 mm

Settlement analysis

The values given above show a clear relationship between the magnitude of the settlement since the construction of the building and the present rate of settlement, similar to that assumed in the analysis of the settlement of the ROMI factory. The continuing settlement process and the related increase in differential settlements are caused by a continuing settlement of the compressible layers. The smaller settlement at the south end of the building is a consequence of the locally better soil conditions. Average rates of settlement, based on different starting-points, are presented in Table I.

TABLE I: Comparison of rates of settlement (in mm/year)

	average from measurements		present rate by extra-polation via Keverling Buisman
	1953-1983	1982-1984	
south end (front)	5	2	2
middle (front)	7	5	3
middle (back)	10	4	4
north end (front)	8	3	3

The results show that the rate of settlement is decreasing as may be expected from the formula of Keverling Buisman. Present rates of settlements, derived from the measurements in the period 1982-1984 and obtained by a logarithmic with time representation of the settlements since the construction, agree rather well, Figure 14. The measurement results seem to indicate that the rate of settlement of the middle part (front) has been increasing over the recent years. In Figure 14 it has been assumed that the point of time t_1 coincides with the point of time of the first measurement. A different time of loading and the presence of a hydrodynamic period has not been taken into account. However, the formula of Keverling Buisman is also very useful in this case for settlement predictions. The expected settlements vary between about 2 and 4 mm/year.

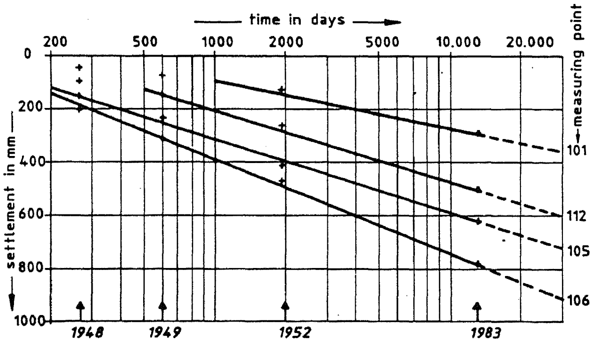

Fig. 14 Time-Settlement diagram

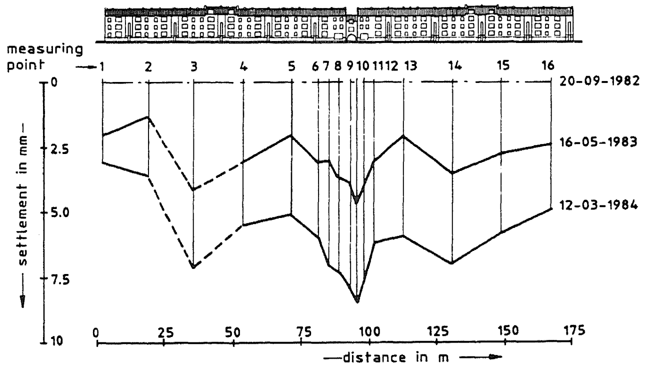

Fig. 13 Settlement of the front side in the period September 1982 up to March 1984

CONCLUSIONS

The settlement of buildings after construction may amount to many decimeters. If this is the case, the building will almost certainly crack, because settlements are never uniform. The causes of settlement may vary. In the present cases the load of sand fill has played the major role in addition to the weight of the building itself. Accurate measurements are essential for the analysis of a settlement process. A period of at least two years is often necessary to establish a rate of settlement with sufficient accuracy. An assumed time-settlement behaviour of a building may deviate from the measured results because of inaccuracies in the measurements, varying groundwater levels and temperature effects during the measurements. A settlement process, once started, continues and can usually be described correctly by means of the settlement formula of Keverling Buisman. The three case studies, described here, indicate that, even 30 years or more after construction, the rates of settlement can be 5 mm/year. They also show that the same ratio exists between the settlement since the construction and the instantaneous rate of settlement for the different measuring points. Measuring data, data about structural history, the building itself and the subsoil are indispensable for back-dating the settlement behaviour of a building since its construction. A complete reconstruction of the settlement history of a building, since the construction, is the best base for predicting settlements. Whether there is an acceleration of the settlement process can be discovered in this way, so that measures can be taken in time.

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