Substructure: Design and construction. Settlements

1 Purpose and scope

Railway installations on soft, compressible ground are often subject to long-term consolidation settlement in the subsoil. Settlement that develops well into the operational phase will be deleterious to the geometric condition of the track and overhead contact line, meaning that the installation has to be more carefully monitored and maintained.

It has been deemed appropriate to introduce settlement requirements, in order to ensure that conditions that may result in any settlement of new tracks are acceptable. This is essential if unforeseen and unacceptably high maintenance of the track and overhead contact line is to be avoided. In addition, the settlement requirements are a means of preventing unnecessarily high construction costs.

This chapter deals with settlement requirements for new railways during the design, planning and operational phases. It also provides a guide report on settlement reduction measures and a description of practical settlement monitoring systems.

2 Application of settlement requirements

The settlement requirements stipulated in these regulations apply to the construction of new K0 lines (i.e. lines with maximum speeds of up to ≥ 145 km/h). The requirements must be applied to the design of new installations and the upgrade of existing sections of line to the K0 standard.

These requirements are expected to lower the cost of constructing sections of line for which soft clayey ground presents a significant problem. Therefore, every attempt must be made to comply with the requirements in a way that results in the lowest possible construction costs. However, a separate financial analysis of the total costs of major construction projects may be required, in order to assess whether the requirements achieve the lowest possible combined construction and operating costs. On the basis of this analysis, the line developer may find it advisable to impose more stringent settlement requirements.

Less stringent settlement requirements than these requirements must not be used as a basis for sections of line that are required to be constructed to the K0 standard.

3 Permissible settlement during operational phase

3.1 Principles

Sections of line on which uneven settlement occurs during the operational phase will require additional inspection and calibration of track and overhead contact line. It is difficult to achieve an acceptable level of settlement during the first few years of an installation's operation, since settlement development in the ground decreases sharply with time.

Settlement develops from the moment backfilling takes place. Settlement occurs slowly in fine-grained ground, but is definitely at its maximum immediately after backfilling. The period of time allowed for settlement before the line becomes operational (t_0) therefore has a considerable impact on settlement development during the operational phase. The effect of this is built into the settlement requirements.

Permissible settlement of the ballast bed during the operational phase is shown in Table 1. This table is fundamental to the regulation's settlement requirements and applies both to the maximum settlement in simple profile and to variations in settlement development of the ballast bed, longitudinally and crosswise. The main emphasis is on ensuring that differential settlement is monitored satisfactorily along and across the track during the first few years of the operational phase, with inspections after three and nine years of operation.

The following principles have been used as a basis for the design of the requirement specifications:

- certain variations of moderate settlement in the simple profile are acceptable, as are certain variations of distortion settlement from one cross-section to another along the ballast bed
- restrictions apply to the amount of average settlement and distortion settlement that is acceptable in a single cross-section
- permissible values indicate how quickly differential settlement, side distortion and moderate settlement may develop over time
- the requirements have been designed for the operational phase; therefore, no settlement requirements have been stipulated for the construction phase (i.e. the period until the track has been laid and calibrated).

Tabell 1: Permissible settling of ballast bed during operational phase

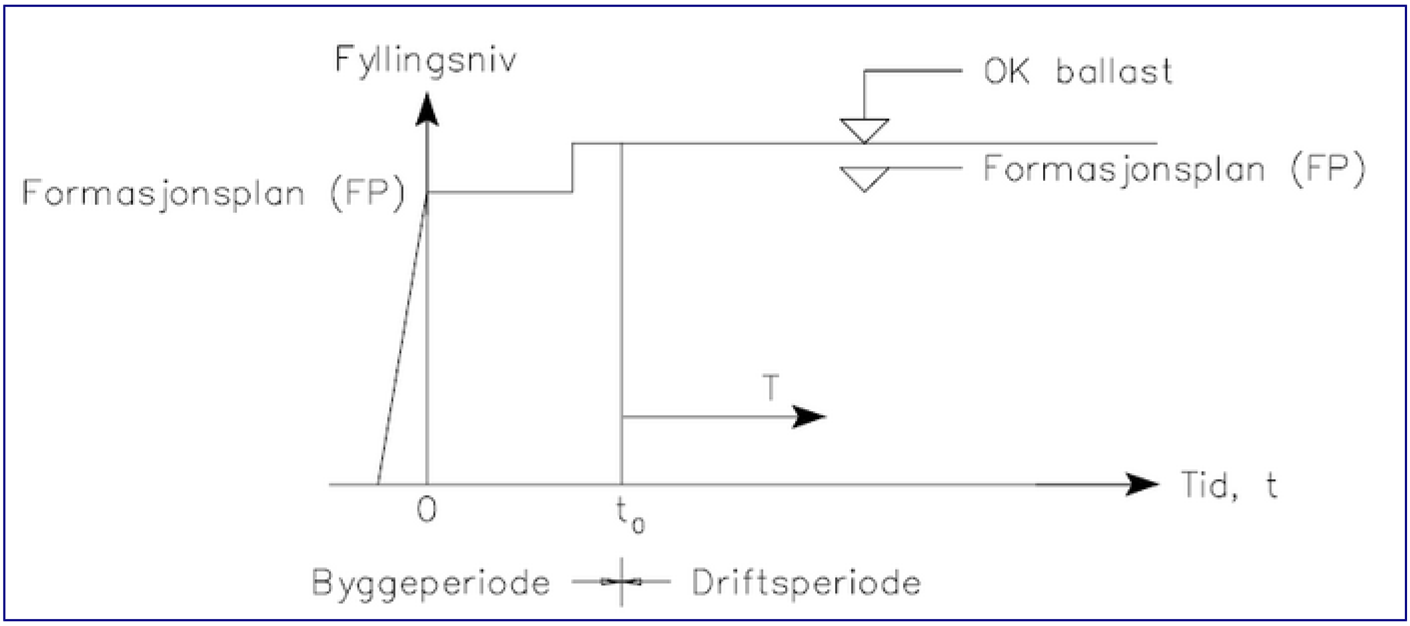
Type of settlement		**Maximum permissible settlement during operational phase**		**Distance between cross-sections** [1)]
		First 3 years of operation	**First 9 years of operation**	
Settlement in simple profile	moderate settlement	24 cm	40 cm	-
	distortion settlement	17‰	28‰	-
Differences in settlement between adjacent profiles	differential settlement (slope)	2.8‰	4.8‰	25 m
		2.2‰	3.6‰	50 m
		1.4‰	2.3‰	100 m
	warping (variation in distortion settlement per 25 metres)	10‰	17‰	25 m
		7.5‰	12.5‰	50 m
		5‰	8‰	100 m

[1)] The settlement requirements for differential settlement and warping depend on the distance between the profiles being assessed. The longer the distance between the sections being assessed, the more stringent the requirements regarding differential settlement and warping between adjacent profiles.

When assessing settlement in a given location, the following times must be clarified:

- time at which settlement begins to develop during operational phase ($t = t_0$, $T = 0$)
- time at which terrain settlement actually begins ($t = 0$, $T = -t_0$)

When backfilling on soft ground, these times are normally defined using Figure 1 as a basis.



Figur 1: Definition of time allowed for settlement during operational phase ($T= t-t_0$) and time allowed for settlement before line becomes operational (t_0)

The length of the period allowed for settlement before the line becomes operational (t_0) has a major effect on settlement development during the first few years of operation. The effect of the length of the construction phase on settlement during the operational phase must therefore always be taken into consideration during the design phase.

Settlement requirements have been stipulated for two fixed times during the operational phase, at the three year and nine year points. Alternative requirements have been specified for differential settlement and distortion settlement, depending on whether the length of the section being assessed is 100 m, 50 m or 25 m. Because differential settlement will develop, the requirements are more stringent for longer sections. The final evaluation of critical sections must normally be based on the requirements specified for length intervals of 25 m.

Sections susceptible to critical settlement variations during the operational phase will often be limited to embankments constructed on varying ground conditions. This applies in particular to transitions from firm ground to soft clayey ground, embankments transitioning to bridges and culverts, and other transitions to permanent structures. The design phase must therefore focus carefully on sections of line with variations in potential settlement, for example during the design of points loops, where access is needed to both tracks at the same time during calibration work.

3.2 Permissible development of differential settlement in longitudinal profile of line

3.2.1 Requirement specification

Table 2 provides settlement requirements with regard to varying settlement in the longitudinal direction of the line.

|-

! rowspan="2" width="150px"| Point at which settlement requirements apply[1)] !! colspan="3"| Permissible differential settlement along length interval ΔL[2)] at relevant time[3)]. Settlement indicated in cm /‰ slope. |- ! ΔL = 100 m !! ΔL = 50 m !! ΔL = 25 m |- | T = 3 years || 14 cm / 1.4% || 11 cm / 2.2‰ || 7 cm / 2.8‰ |- | T = 9 years || 23 cm / 2.3 % || 18 cm / 3.6‰ || 12 cm / 4.8‰

|}

[1)] The time (T) is calculated from the moment the track has been calibrated, normally when the line becomes operational.

[2)] If the settlement requirement is found to have been fulfilled for one of the three length intervals indicated (e.g. ΔL = 100 m), the requirement for the remaining length intervals (e.g. ΔL = 50 m and ΔL = 25 m) may normally be regarded as having been fulfilled.

[3)] If it can be verified that the differential settlement is less than 70% of what is permissible at the point T = 3 years, the requirement for T = 9 years may also be regarded as having been fulfilled.

3.2.2 Initial values and use of the requirements

The permissible differential settlement along the ballast bed varies with, and is governed by:

- period of assessment
- length of period allowed for settlement before line becomes operational (t_0)
- length of line being assessed (ΔL)

Permissible differential settlement is indicated for three years and nine years after line becomes operational. For sections that are found to have achieved clearly less differential settlement than what is permissible (< 70% of what is permissible) in the period up to and including three years of operation, it is not normally necessary to verify that settlement is also acceptable at the later settlement stage. For sections requiring special measures in order to satisfy the settlement requirement, surveys must always be performed for both of the periods indicated.</nowiki>

There is an option to verify that differential settlement is acceptable for alternative length intervals, ΔL, 100 m, 50 m and 25 m respectively. The requirements are normally regarded as having been fulfilled when one of the length intervals has been found to be satisfactory. However, the requirements are more stringent when longer length intervals are assessed. For sections requiring special measures in order to satisfy the settlement requirement, the length interval ΔL = 25 m must be used as a basis.

3.3 Permissible variation of side distortion along the ballast bed

3.3.1 Requirement specification

Table 3 provides settlement requirements with regard to varying side distortion along the ballast bed.

Tabell 4: Permissible development of varying side distortion (distortion settlement) along newly installed lines

Point at which settlement requirements apply[1)]	**Permissible differential settlement along length interval ΔL[2)] at relevant time[3)]. Settlement indicated in cm /‰ slope.**		
	ΔL = 100 m	**ΔL = 50 m**	**ΔL = 25 m**

T = 3 years	5‰	7.5‰	10‰
T = 9 years	8‰	12.5‰	17‰

1) The time (T) is calculated from the moment the track has been calibrated, normally when the line becomes operational.

2) If the settlement requirement is found to have been fulfilled for one of the three distances indicated between adjacent profiles (e.g. ΔL = 100 m), the requirements for the remaining profile distances (e.g. ΔL = 50 m and ΔL = 25 m) may normally be regarded as having been fulfilled.

3) If it can be verified that the distortion settlement is less than 70% of what is permissible at the point T = 3 years, the requirement for the next inspection at T = 9 years may also be regarded as having been fulfilled.

3.3.2 Initial values and use of the requirements

The permissible difference in distortion settlement between adjacent profiles varies with, and is governed by:

- period of assessment
- length of period allowed for settlement before line becomes operational (t_0)
- length of line being assessed (ΔL)

Permissible difference in distortion settlement is specified for three and nine years into the operational phase. For sections that are found to have achieved less distortion settlement than what is permissible (< 70% of what is permissible) after three years, it is not necessary to verify that distortion settlement is acceptable at the later settlement stage. For sections requiring special measures in order to satisfy the settlement requirement, surveys must always be performed at both of the times indicated.

There is an option to verify that the differences in distortion settlement are acceptable for alternative length intervals, ΔL, 100 m, 50 m and 25 m respectively. The requirements are normally regarded as having been fulfilled when one of the length intervals has been found to be satisfactory. However, the requirements are more stringent when longer length intervals are assessed. For sections requiring special measures in order to avoid major variations in distortion settlement, the interval ΔL = 25 m length must be used as a basis.

3.4 Maximum permissible settlement in simple profiles

3.4.1 Requirement specification

Table 4 provides settlement requirements with regard to settlement in simple profiles.

Tabell 5: Accepted maximum settlement development in simple profile (cross-section) of newly laid ballast beds

Point at which settlement requirements apply[1)]	Permissible moderate settlement in simple profile[2)]	Permissible distortion settlement (side distortion) in simple profile[3)]
T=3 years	24 cm	17‰
T=9 years	40 cm	28‰

1) The time (T) is calculated from the moment the track has been finally calibrated, normally when the line becomes operational.

2) If it can be verified that the distortion settlement is less than 70% of what is permissible at the

point T = 3 years, the requirement for the next inspection at T = 9 years may also be regarded as having been fulfilled.

3.4.2 Initial values and use of the requirements

Permissible moderate settlement and distortion settlement in simple profiles at locations along the ballast bed vary with and are governed by

- period of assessment
- length of period allowed for settlement before line becomes operational (t_0)

Permissible moderate settlement and distortion settlement in cross-sections is indicated for three years and nine years after line becomes operational. For sections that are found to have achieved less differential settlement than what is permissible (<70% of what is permissible), three years after the line becomes operational, it is not necessary to verify that settlement is also acceptable at the later settlement stage. For sections requiring special measures in order to satisfy the settlement requirement, surveys must always be performed at both of the times indicated.

3.5 Acceptable difference between requirement and actual settlement

When designing railway installations, the settlement requirements stipulated in Table 2, Table 3 and Table 4 must be regarded as a target for critical sections. This means endeavouring to achieve the following:

- significantly greater settlement than what is permissible does not occur on any sections
- settlement occurs approximately as permitted on critical sections

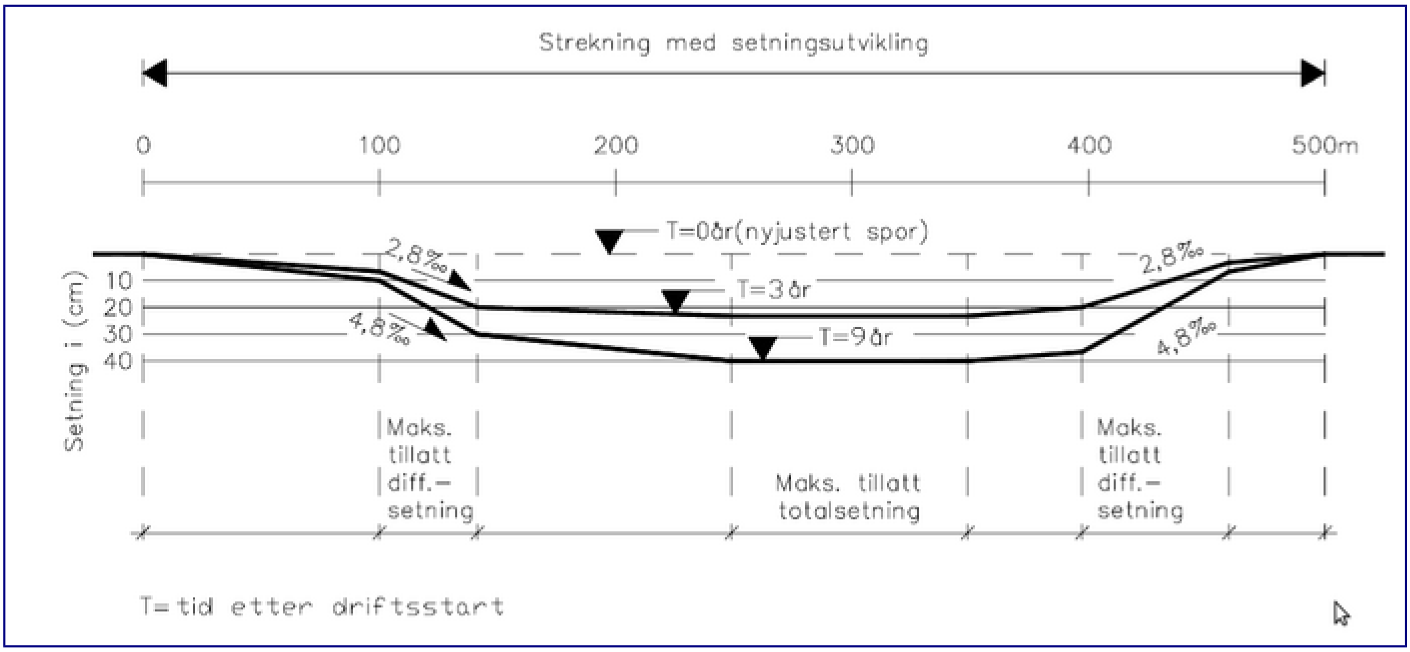
A difference of up to ± 25% between predicted and actual settlement is acceptable. However, the construction client may specify more stringent requirements for certain sections.

The geotechnical designer must notify the building contractor if the predicted settlement on critical sections is considered to be outside an acceptable limit of certainty.

3.6 Illustration of permissible settlement development during operational phase

3.6.1 Permissible settlement in longitudinal profile

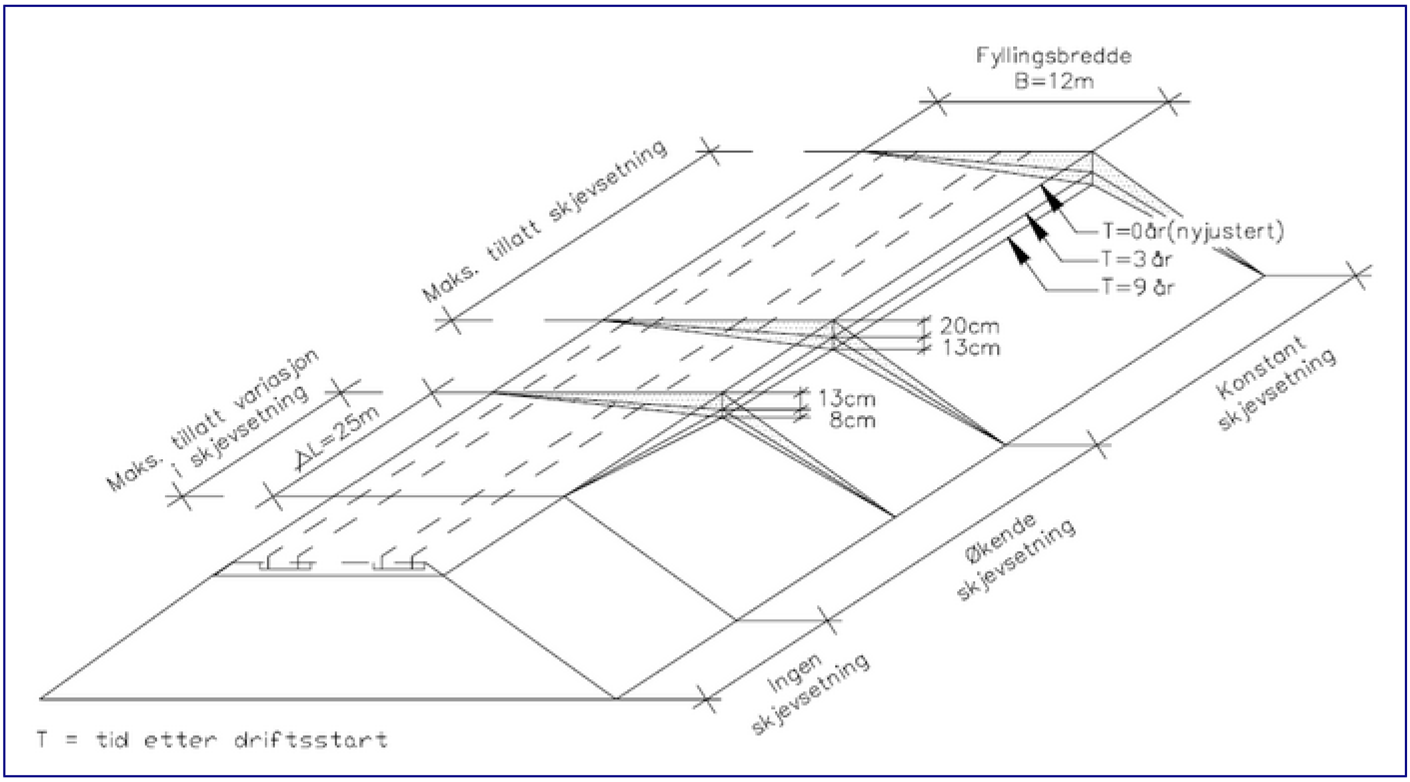
Accepted differential settlement development and maximum settlement development along newly laid ballast beds in accordance with the tables is illustrated in Figure 2. The settlement indicated in the figure is expected to result in the need for two or three calibrations of the track and overhead contact line during the first nine years of operation. The settlement shown therefore applies to an uncalibrated line.



Figur 2: Longitudinal profile of section with maximum permissible settlement development and differential settlement during the operational phase

3.6.2 Permissible distortion settlement

Accepted side distortion development (distortion settlement) across newly laid ballast beds in accordance with Table 3 and Table 4 is illustrated in Figure 3. The side distortion indicated in the figure is expected to result in the need for two or three calibrations of the track and overhead contact line during the first nine years of operation. The settlement shown therefore applies to an uncalibrated line.



Figur 3: Example of section with maximum permissible distortion settlement development during operational phase

3.7 Requirement to increase width of formation level

If settlement greater than 20 cm is expected, and as a result, there is a possibility that the track may have to be raised during the operational phase, an increase in the width of the formation level must be considered, ensuring that the requirements regarding shoulder width, water channel length, location of cable ducts, etc. will be complied with.

3.8 Settlement requirements in relation to the railway's mast foundations

A number of settlement requirement provisions regarding mast foundations must be taken into consideration when designing and constructing railway installations in accordance with the regulations.

The following three dimensions must be used as a basis for the foundations of overhead contact line masts, irrespective of the local conditions:

1. respective settlement development in mast foundations and ballast bed during operational phase are as equal as possible
2. mast foundations settle less than ballast bed foundations
3. minimum possible settlement of mast foundations during operational phase

The choice of mast foundation dimensions must be based on Table 5.

Tabell 6: Preferred dimensions for mast foundations, irrespective of local conditions

Length of section subject to settlement	**Ballast bed settlement**	**Mast foundation dimensions**		
		1	**2**	**3**
Shorter than approx. 150 m	Achieved less than what is permissible[1)]		(x)	x
	Approx. as permitted[2)]		x	(x)
Longer than approx. 150 m	Achieved less than what is permissible[1)]	(x)	x	
	Approx. as permitted[2)]	x	(x)	

[1)] Ballast bed settlement is acceptable without the use of special settlement reduction measures

[2)] Critical section based on ballast bed settlement

For short sections subject to settlement (shorter than approx. 150 m) the mast foundations should preferably settle less than the track during the operational phase. Where foundation conditions permit, the foundation method chosen should result in the least possible settlement of mast foundations during the operational phase.

For long sections subject to settlement (longer than approx. 150 m), depending on the foundation conditions, the foundation method chosen must result in mast foundation settlement equal to or less than that of the ballast bed. Every effort must be made at all times to avoid mast foundations settling more than track foundations.

On long sections subject to settlement, the aim should be to achieve a harmonised settlement development in mast foundations during the operational phase, as defined in Alternative 1. Extensive measures to reduce settlement, particularly in mast foundations, are therefore rarely relevant for long sections.

4 Geotechnical design requirements

The requirements specified for controlled deformation development involve ensuring that the problem of settlement is addressed systematically and purposefully during the design phase.

Long-term settlement development during the operational phase must be calculated when designing foundations according to current regulations. Since the length of period allowed for settlement before a line becomes operational (t_0) has a major effect on settlement development during the first few years of operation, designers must always take the construction time (and any dormant period that would extend this) into consideration when preparing settlement predictions for the operational phase.

Once the settlement requirements have been defined, the design work should be limited to planning to keep settlement within specified limit values, stated as permissible settlement after three and nine years of operation.

The following sections contain important prerequisites that must normally be used as a basis for the geotechnical element of the design work.

4.1 Geotechnical feasibility studies and analyses

The purpose of geotechnical feasibility studies is to obtain a sufficiently reliable geotechnical basis for design. Feasibility studies for railway installations must provide a basis from which settlement and stability may be calculated. Both problems must therefore be taken into consideration during the planning process and when carrying out ground surveys.

As far as practically possible, ground surveys and geotechnical design must be carried out in phases. This is to ensure that the scope of the surveys is suitable for the level of ambition, thereby avoiding unnecessarily detailed surveys of sections on which settlement and stability are not a problem. Objectives suitable for phased ground surveys and settlement calculations are illustrated in Table 6.

Tabell 7: Outline of system of phased ground surveys and settlement assessments

Phase	Objective of ground surveys	Relevant settlement calculations (and stability calculations)
1	Identify points/sections with potential settlement problems	Estimated calculations with expected characteristic parameters
2	Clarify where ground reinforcement measures are required	Sensitivity analyses with variations of uncertain parameters and calculation assumptions
3	Provide a basis for final choice and design of reinforcement measures	Calculations of alternative foundation solutions

Experience shows that there should be a particular focus on certain areas and conditions during the design phase, for example:

- areas where the ground conditions change, for example from clay/silt to frictional soil or moraine, and in transitions to rock
- clay with high sensitivity (this could be artesian pore water pressure caused by underground ridges with water-bearing frictional soil, or coarser layers against protrusions of rock)
- near watercourses and in areas where organic clay occurs

4.2 Settlement requirements adapted to suit level of ambition

The use of the requirements regarding differential settlement and side distortion at various design phases must be adapted to suit the level of ambition of each stage in the design process. Standard methods of adapting the settlement criteria to suit the level of ambition are shown in Table 7.

Tabell 8: Recommended use of settlement requirements at various stages in design phase

Level of ambition of geotechnical studies and analyses	Settlement requirements to be used as a basis[1)]		
	Requirement specified for ΔL = 100 m	Requirement specified for ΔL = 50 m	Requirement specified for ΔL = 25 m
a) Potential problem points identified	x	(x)	
b) Critical sections identified (that probably require special measures)		x	(x)
c) Choice of groundwork measures for critical sections			x

[1)] Cf. requirement specifications in Table 2 and Table 3

4.3 Settlement equalisation of critical sections

Settlement reduction measures must normally only be used on sections on which there is expected to be major differential settlement, distortion settlement or maximum settlement greater than that indicated in Table 1. In order to avoid unnecessarily high costs for groundwork measures on critical sections, the following principles must be observed:

- where maximum settlement is not critical, essential settlement equalisation must be given a higher priority than general settlement reduction
- economically favourable measures should be chosen to achieve essential settlement reduction and settlement equalisation
- the construction phase should be used for settlement equalisation wherever possible

4.4 Use of settlement reduction measures

Planning settlement reduction measures is an integral part of design work. In principle, there is a choice between three types of measures, grouped according to function/effect:

1. Reduce additional loads on soil layers subject to settlement
2. Increase soil stiffness
3. Increase settlement development during construction phase

A summary of the most appropriate settlement reduction methods and their primary and secondary effects is shown in Table 8. In some cases, it may be necessary to combine several methods. The most appropriate combinations of measures are preloading combined with vertical drainage and replacing soil with lightweight fill (the latter if the aim is to achieve a fully compensated foundation). On the trial section of the Hovedbanen Line, lime cement piles have been used in combination with lightweight fill.

Tabell 9: Effects of settlement reduction measures

Measure/method	Effects		
	Reduced additional load	Increased soil stiffness	Increased settlement development during construction

			phase
Longer dormant period for embankments		B	A
Soil replacement		A	
Preloading		B	A
Lightweight fills	A		
Lime cement piles		A	B
Vertical drainage		B	A
Electro-osmosis		A	B
Piles under embankment	A		
Bridge	A		

A: primary effect

B: secondary effect

The need for settlement reduction measures must be established on the basis of calculations and assessments of expected settlement, measured against specified settlement requirements. Measures will normally primarily be required in the following locations:

- Sections where ground conditions change, particularly areas abutting solid rock
- Where embankments terminate against solid structures (bridges, culverts)
- Short sections of embankment
- Sections of embankment with extreme height variations
- Sections that have previously been filled
- Sections over streams and rivers

The choice and design of measures must be evaluated on an individual basis, preferably after assessing several alternatives from financial and technical perspectives. The required scope of measures, and thereby also the costs, increase markedly with embankment height. In order to allow sufficient time for settlement, it is therefore essential for high embankments to be constructed as early as possible, and for optimal measures to be used for these embankments. Experience has shown that more extensive measures are required to equalise transitions between soft and firm ground than to equalise differences in settlement caused by varying embankment heights.

5 Settlement monitoring

5.1 General

It is important to obtain an experience base regarding settlement on new sections of line.

Therefore, the work of designing new sections of line on soft ground must include the evaluation of a system for monitoring settlement during the construction and operational phases. The system should be described in the tender documents.

Settlement monitoring will provide a basis for

- monitoring settlement during the construction phase, particularly during phased embankment construction
- comparing actual and predicted settlement
- studying the effect of various settlement reduction measures
- monitoring settlement development between ballast beds and masts
- monitoring settlement development over time
- monitoring the relationship between track defects and settlement

- identifying problem areas for operation and maintenance resulting from settlement
- evaluating the settlement requirements

Alternative methods of settlement monitoring include obtaining measurements from special tubes laid under the entire width of the embankment (across the entire cross-section), monitoring settlement at specific points, as well as taking levels and measurements in relation to the line's geodetic survey markers.

5.2 Settlement monitoring using settlement tubes

In order to be able to monitor settlement development on particularly vulnerable sections, and to gain experience regarding any settlement reduction measures that have been implemented, tubes can be laid to measure settlement underneath structures such as embankments.

Tubes made of, for example, flexible polyethylene, with a diameter of at least 75 mm may be used. These must have a smooth inner surface. The tube ends must be fitted with removable caps.

The tubes may be laid underneath the embankment on natural ground, thus completely eliminating the effect of any settlement in the embankment above. A gravel packing should be used around the tubes to protect them from damage. The location of the tube ends and the length of the tubes, etc. must be precisely indicated.

Because of various construction factors, it can often be easier to achieve this once the embankment has been constructed up to formation level. As a rule, settlement in the embankment itself will be much less common than settlement in the subsoil. Thus, taking measurements from the formation is generally sufficient. However, this means that any settlement that may have developed during the embankment's construction up to formation level is not monitored. Therefore, each location must evaluated on an individual basis and the most practical solution decided upon. Irrespective of which solution is used, the tubes should be laid under the construction works as early as possible.

Measurements may be taken using a hydraulic settlement meter, which in principle is a tube filled with liquid, with a sensor at the end. The height difference between the sensor and the meter is logged as the sensor is pushed into the tube.

5.3 Measurements

Since the settlement requirements concentrate on distances of 25, 50 and 100 m as intervals for settlement calculations, the settlement measurements should also be performed using those same intervals, in order to obtain a basis that can be compared with the calculations that have been performed.

Measurements should begin as early as possible, since settlement often occurs most rapidly in the earliest phases. It is particularly important to take a reference measurement at a very early stage, so that this can act as a 'zero point' for subsequent measurements.

Measurements must be taken most frequently during the construction phase and early in the operational phase; they may later be reduced to the inspection points of three and nine years of operation, adjusted in relation to any tendencies in settlement development.

Measurements in relation to randomly selected 'fixed points' can often prove to be problematic, since these markers may disappear underneath the construction works. It is therefore important to determine the height of fixed markers as early as possible in order to establish reliable, exact heights of settlement tubes, settlement bolts and plates. Where permanent geodetic markers are installed along the line, these may be considered for use as height references for settlement measurements.