A contribution to the analysis and the design concept of piled raft foundations

Article sur le brouillon de la preuve et du dimensionnement des fondations sur pieux et sur radiers

D.Placzek – *ELE, Erdbaulaboratorium Essen, Germany*
E.Jentzsch – *VEAG, Vereinigte Energiewerke AG, Berlin, Germany*
K.Schulte – *ELE, Erdbaulaboratorium Essen, Germany*

ABSTRACT: For about two decades piled raft foundations are establishing itself as an innovative element within foundation engineering. Typically, they are selected with the objective to increase the load bearing capacity of the structure and to reduce the settlements and settlement differences in highly compressible ground. The paper presents a case study of founding a massive lignite power station which unusually high vertical loads in soft ground. The operational requirement of minimising settlements and settlement differences was achieved by use of a pile raft foundation. Special emphasis is put on performance monitoring carried out in various construction phases and on a comparison of the predicted and observed settlements of the piled raft foundation in response to loading.

RÉSUMÉ: Depuis une période d' environ 20 ans, on utilise les fondations sur pieux et sur radiers comme une nouvelle variation de fondation dans le but d' accroître la portance, en face d' une fondation superficielle, et de réduire des tassements et des tassements différentiels dans le cas de sous-sols de construcion fortement compressibles. Dans le cas présenté de la construction d' une centrale thermique au lignite avec des influences verticales de charges exceptionellement grandes, il était nécessaire de minimiser les tassements et les tassements différentiels. Cet article communique les résultats des mesures de la compression du sous-sol qui ont accompagné la construction jusqu' à la mise en activité de la centrale. Il compare aussi le comportement à l' appui réel et le comportement à l' appui prévu de la fondation sur pieux et sur radiers.

1 INTRODUCTION

Piled raft foundations (PRF) are composite geotechnical structures which are characterised by their capability of sharing loads between their respective foundation components, i.e. piles and raft. They are particularly suitable in supporting major structures with concentrated loads in highly compressible ground. In comparison to more traditional foundation designs, piled raft foundations usually lead to a reduction of settlements, settlement differences, tilt and raft bending moments. They are particularly economic and often statically advantageous (Katzenbach et al., 1997).

In Germany piled raft foundations are designed and constructed for about 20 years. The first projects were in the City of Frankfurt/Main in which high-rise buildings were founded in over-consolidated clay (Lutz et al., 1996; Katzenbach, 1993).

Since the early beginnings piled raft foundations have steadily gained acceptance with a particularly significant increase in recent years. This development has lead to the demand for specifying generally acceptable design standards, a demand which triggered intense discussions within the Profession about the load bearing capacity of PRF (Thaher, 1995; Katzenbach and Moormann, 1999; Katzenbach et al., 1999).

Figure 1. View of the main buildings of the new Boxberg power station

Based on both research and practical experience gained with PRF so far, "Guidelines for the Design, Dimensioning and Construction of Piled Raft Foundations" were drafted by the DIBt, the Deutsches Institut für Bautechnik in Berlin (National German Institute for Construction Techniques). The draft was recently published by Hanisch et al., 2000.

Against this background this paper reports on the performance of the PRF of a massive new 915 MW lignite power block erected near the township of Boxberg. The owner of the power station is the Vereinigte Energiewerke AG (VEAG) in Berlin.

This project was already introduced by Placzek and Jentzsch (1997) on the occasion of the XIV ICSMFE Conference in Hamburg, at which also some first results were presented on the settlements occurring in the early construction phase. In the meantime the construction was completed and the power station commissioned in October 1999. In this contribution additional information will be presented with particular emphasis on a comparison between monitored and predicted settlements of the PRF. In this way it is aimed at contributing towards a profound judgement of the drafted PRF Guidelines. In particular it is of interest in how far the design concept of the Guidelines can be generalised to regions beyond that of the classical PRF-region of Frankfurt.

2 SETTING

2.1 *Above-ground structures*

A new 915 MW lignite power station was recently built near the township of Boxberg in the east German state of Brandenburg. The main buildings of the station include the power house, the heavy-duty bunker, the switch substation and the 135 m high boiler house with a number of slender stair towers. The buildings are narrowly spaced and transfer high loads onto the foundation and into the ground. They cover an area of about 135 m x 80 m. Figure 1 depicts the main buildings of the new power station.

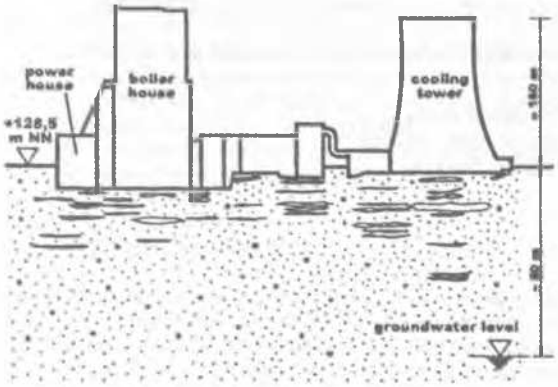


Figure 2. Cross-section through the subsoil and building

2.2 *Subsoil conditions and foundation*

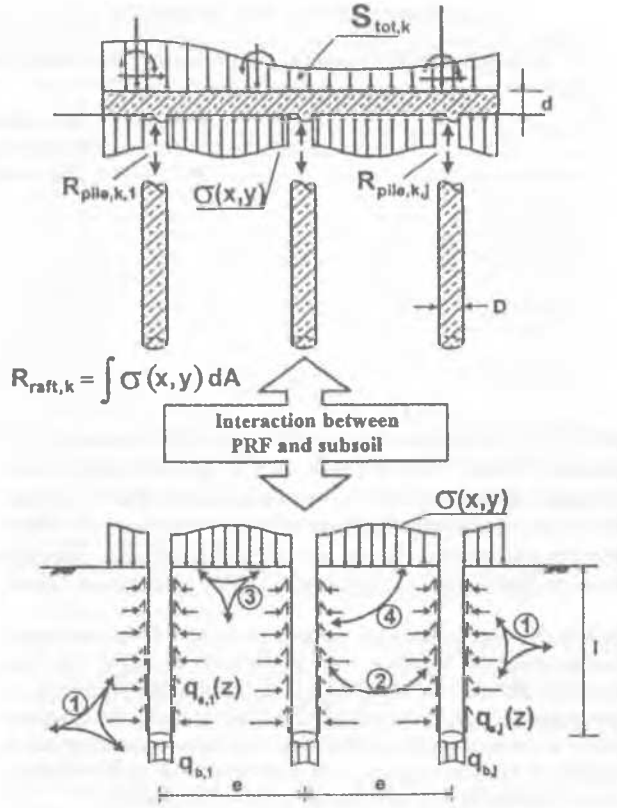
Project-specific investigations revealed subsoil conditions as indicated in Figure 2. Beneath a thin, approximately 1 m thick top layer of fill there are naturally deposited layers of slight to heavily silted sand. Thin lenses of silt and also of organic material are embedded within the sand without forming any definite or continuous layers. The maximal thickness of the lenses is approximately 1 m. The sand fraction generally is fine to coarse with a tendency to fine to medium fractions in the upper layers. In reverse, in the deeper layers the sand tends to become more coarse-grained and to locally transform into a gravel-sand mixture or even into a gravel. This increase of the grain size is generally associated with a decrease in the occurrence of the lenses of cohesive and organic material. Overall, the subsoil conditions are comparatively uniform and of a high degree of homogeneity.

Soil mechanically critical for the foundation are the cohesive, partly organic lenses of up to about 1m thickness. As mentioned earlier these lenses are repeatedly embedded within the sand down to a depth of about 20 m. Clearly, they control the compressibility of the entire subsoil beneath the new power plant buildings. If they occur in close proximity to the foundation, they also are decisive for the load-bearing capacity of the buildings. At a first glance it is evident that the concentrated cluster of heavy-duty buildings and its associated extremely high loads require a surface foundation in the form of a continuous raft. Initial estimates revealed relatively high amounts of settlements in the order of 10 cm for the main buildings and of some 15 cm for the edges of the rafts where the external stair towers are located. This amount and distribution of settlements were highly incompatible with the constraints from the power plant operations. Between the four heavily loaded pillars of the boiler, for instance, settlement differences of only up to 1 cm could be tolerated. At an axial distance of about 33 m between the respective pillars this, in turn, means that a tilt of less than 1 : 3 300 had to be maintained. It was found that this requirement could not be met by a continuous reinforced concrete raft even if 5 m thick. This situation with the requirement for very small settlement differences led to the selection of a PRF for the main buildings. It was decided to accompany the selection of this type of foundation with a comprehensive monitoring programme.

3 BASIC CONSIDERATIONS ON THE LOAD BEARING CAPACITY OF PILED RAFT FOUNDATIONS

3.1 *Concept and mechanisms*

The load bearing behaviour of a PRF is characterised by the circumstances that the two foundation components, piles and raft, are participating in the transfer of loads from the buildings into the ground. The raft, which usually is subject to the full loads of the building, is distributing the loads partly directly into the ground by means of contact pressures σ and partly onto the pile



Legend:
① Pile - soil interaction
② Pile - pile interaction
③ Raft - soil interaction
④ Pile - raft interaction

Figure 3. Piled raft foundation as a composite geotechnical structure and interaction mechanisms between the support elements and the ground which are relevant for the load bearing capacity of the PRF (out of Hanisch et al., 2000)

heads. The degree of the load distribution depends on the stiffness of the various support elements, in particular on the bending stiffness of the raft and on the axial stiffness of the pile, the latter being controlled by the portion of skin and end bearing resistance of the piles.

In a PRF it is predominately the piles which contribute to a reduction of settlements. The portion of the load, which is directly transferred into the ground by means of contact pressures, is significantly reduced when compared with a simple raft foundation. This causes an equally significant reduction of the settlements in the first instance. Overall, in a PRF there is a complex interaction mechanism prevailing between the various foundation elements and the ground as indicated in Figure 3.

The sum of the characteristic values of all actions S_{tot} from the building must be compensated by the characteristic value of the total resistance R_{tot} of the PRF.

The characteristic value of the total resistance R_{tot} of the PRF is made up of the sum of the characteristic value of the resistance of the piles ΣR_{pile} and the characteristic value of the resistance of the raft R_{raft}. The latter is equal to the contact pressure σ (x,y) integrated over the entire area of contact between the raft and the subsoil.

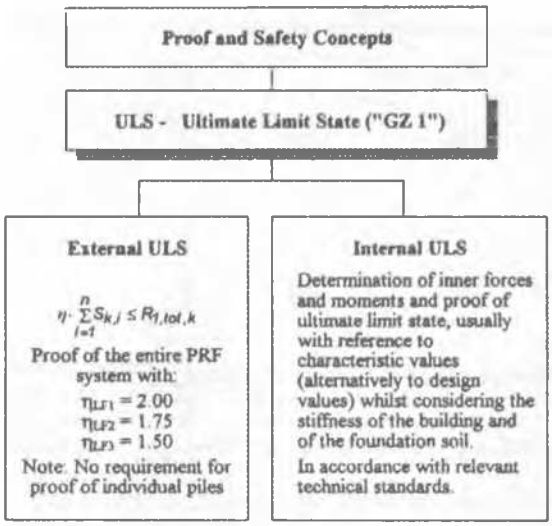
It is

$$R_{tot} = \Sigma R_{pile} + R_{raft} \quad (1)$$

where:

$$R_{pile} = R_b + R_s \quad (2)$$

R_b = characteristic value of pile base resistance
R_s = characteristic value of the skin friction resistance of the pile



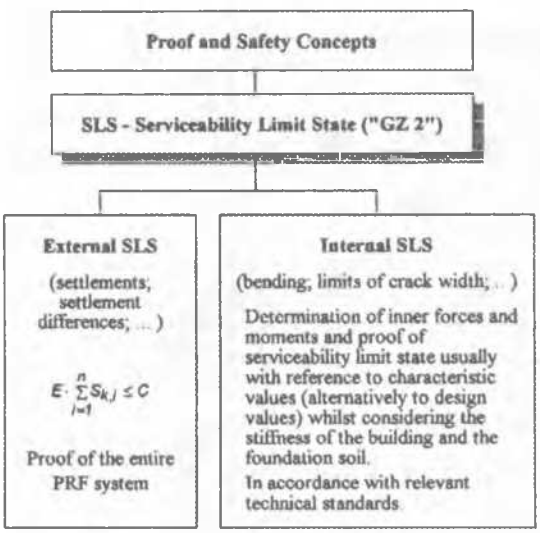
η = factor of global safety for external ULS
$S_{k,i}$ = characteristic value of an action i
$R_{1,tot,k}$ = characteristic value of the total resistance of a PRF for ULS

Figure 4. Analysis of the Ultimate Limit State (ULS) (after PRF Guidelines; Hanisch et al., 2000)

The load bearing mode of a PRF is characterised by the piled raft coefficient α_{PRF}. This coefficient is the proportion of the characteristic values of the pile resistance in relation to the total resistance of the PRF. It is defined as follows:

$$\alpha_{PRF}(s) = \frac{\Sigma R_{pile}}{R_{tot}} \qquad (3)$$

Within a PRF, the number and distribution of piles is essentially controlled by the type of piles, by the raft sections which are subject to particularly high loading from the building and by the load bearing capacity of the piles. In normal circumstances the load bearing capacity of the piles should be fully exploited right up to R_{pile}.



E = action effect at SLS
$S_{k,i}$ = characteristic value of an action i
C = resistance property for SLS

Figure 5. Analysis of the Serviceability Limit State (SLS) (after PRF Guidelines; Hanisch et al., 2000)

3.2 *Proof and safety concepts of a piled raft foundation*

Generally, proofs of the PRF to comply with the Ultimate Limit State (ULS) are required for both external and the internal cases. Furthermore, a proof of the Serviceability Limit State (SLS) is essential. The External ULS describes the load bearing capacity of the soil when in interaction with the PRF, whereas the Internal ULS is referring to the limiting conditions of the PRF itself, in particular its components piles and raft.

In referring to the above-mentioned drafted "Guidelines" Figures 4 and 5 elaborate the respective concepts in schematic flow diagrams.

4 LAYOUT OF THE PILED RAFT FOUNDATION

Concrete vibration piles, System Preussag (Placzek 1994) were employed in the project. For the sake of quality assurance a pile test field was installed ahead of construction. In the tests the spacing between the piles was closely investigated and a selection made against the requirements of the pile driving operations and of the results of the test trials with regard to the load bearing and settlement behaviour of the tested piles.

Figure 6 shows the result of the load test trial of Pile P 2. In the trial a maximal pile resistance of R_{max} = 2580 kN was measured at a settlement of the pile head of s = 17 mm. The ultimate pile resistance was found by hyperbolic extrapolation to be R_l = 3 300 kN at an associated ultimate settlement of s_l = 20 mm. From these tests the spacing a of the piles was set to be between a = 1.9 m and 3.0 m.

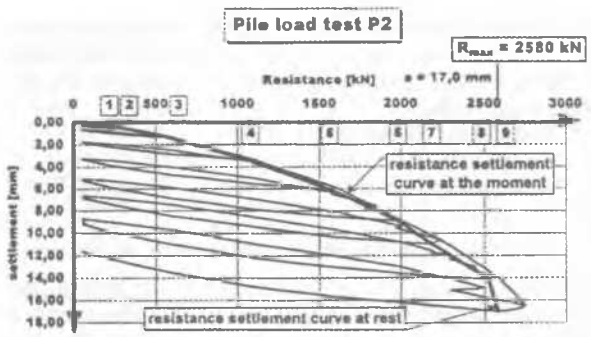


Figure 6. Resistance versus settlement curve of the test trial for Pile P 2

With the selection made with respect to number and spacing of the piles the majority of the building loads are transferred into the ground via the piles. This proportion was estimated to be in the range of 85% of the total building loads. The remaining 15% are transferred into the ground via contact pressure of the raft.
The average thickness of the raft is in the range between d = 2.0 m for the power house and 3.5 m for the boiler house. Locally, e.g. in the area of the staircase towers, the raft thickness is increased to d = 5.0 m. The reinforcement selected amounted to between As = 50 cm² and As = 450 cm² in both longitudinal and cross directions. The computed maximal elastic bending of the raft amounted to 3 to 4 cm.

5 PERFORMANCE MONITORING

5.1 *Monitoring Programme*

For verification of the load-settlement behaviour of the structure a comprehensive monitoring programme was designed and implemented. The monitoring intervals were closely adjusted to the procedures and overall progress of the construction. Besides geodetic settlement measurements, the deformational response of the ground due to loading from the buildings was monitored both in horizontal and vertical directions by means of inclinometer and extensometer.

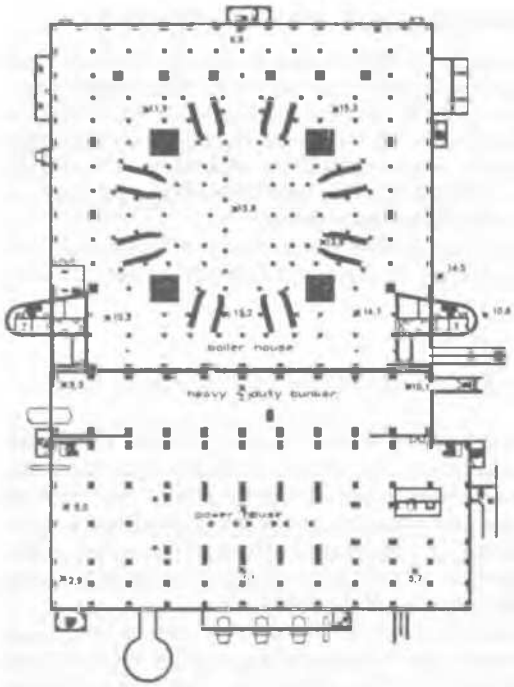


Figure 7. Measured settlements after concreting of the foundation raft (Phase 1: June 1996).

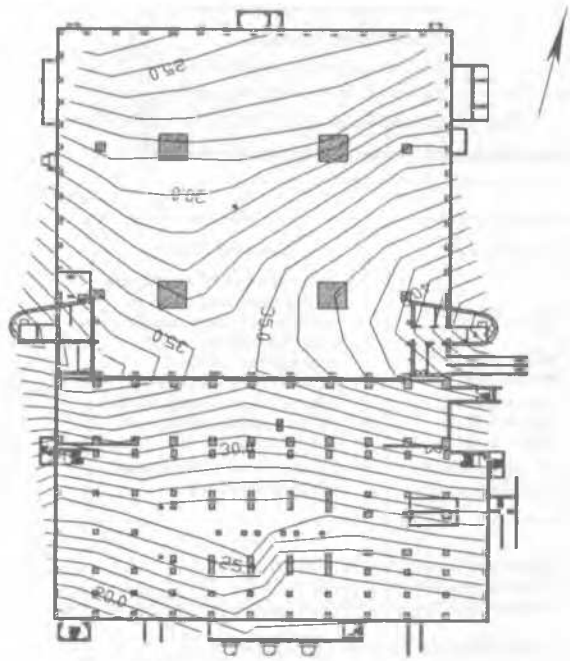


Figure 8. Total settlements measured after completion of the building shells (Phase 2: April - June 1997).

5.2 *Monitoring results*

In the following typical results are presented with particular emphasis to the settlement behaviour of the PRF and of the pillars of the boiler house. Three construction and loading phases are considered as follows:

1. Completion of the raft foundation
2. Completion of the shells of the buildings
3. After commissioning with the plant in operation.

5.2.1 *After completion of the raft and building shells*

For the determination of the settlements in response to the weight of both the raft and the above-ground structures a total of 20 high-precision settlement gauges was installed after the preparation of the foundation level but prior to the placement of the raft. This set-up allowed the determination of the settlements caused by the raft (stage June 1996). Figure 7 shows the measured settlements. They are of the order of s ≅ 7 to 15 mm in the area of the boiler house, of s ≅ 3 to 10 mm in the area of the heavy-duty bunker and of s ≅ 3 to 8 mm in the power house area.

In course of the further construction and prior to the erection of the buildings, the settlement gauges were replaced by settlement bolts with a switch-over to geodetic monitoring. The construction of the shells of the buildings was completed between April and June 1997. The resulting total settlements are graphed in Figure 8 in form of isolines.

It can be depicted that in the areas of the boiler house and of the staircase towers the settlements are in the order of s ≅ 25 to 35 mm. In the areas of the heavy-duty bunker and of the power house they are in the order of s ≅ 20 to 30 mm.

5.2.2 *After completion of the buildings*

At the end of 1999 all buildings including their internal structures were essentially complete so that the power plant could be commissioned in 2000. The measurements carried out in October until December 2000 yielded settlements which are graphed in Figure 9.

It can be depicted that in the areas of the boiler house the settlements are now amounting to the order of s ≅ 30 to 50 mm. In the areas and of the staircase towers they are in the order of s ≅ 50 to 55 mm, in that of the heavy-duty bunker of s ≅ 35 to 45 mm and in the power house area of s ≅ 20 to 35 mm.

As mentioned earlier the main reason for selecting a PRF were stringent requirements of the power plant operations which specified maximally tolerable settlement differences of Δs ≤ 10 mm.

As was proven by settlement monitoring, this requirement was met right throughout the Phases 1 to 3. Table 1 compiles the total settlements measured in the respective foundations of the 4 pillars of the boiler frame. Note that in this compilation no consideration was made of the fact that, prior to the construction of the frame, the height of each boiler footing was adjusted to the settlement differences which had already occurred at this point in time (in May 1997: Δs ≅ 1.5 to 6,5 mm). It turned out that after commissioning of the plant (measurement in October 2000) the

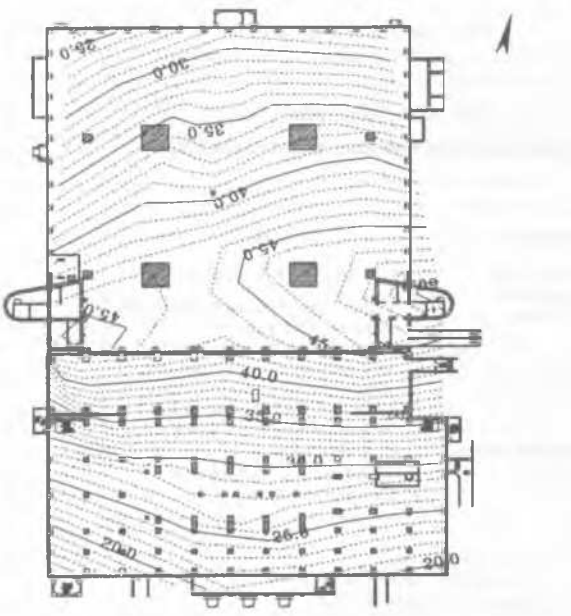


Figure 9. Total settlements measured after commissioning of the plant (Phase 3: October – December 2000).

Table 1. Measured settlements of the boiler footings

Pillar of the Boiler Measuring Point	Settlements [mm] 5 / 1997 (*)	10 / 2000 (**)
101074	32.3	43.8
101032	29.2	37.4
101034	30.7	38.9
101076	36.6	47.0

(*) Time of adjustment of the boiler footings
(**) Plant in operation

settlement specifications were also fully met. The total settlement of the footings was in the order of $s \cong 40$ to 50 mm with associated settlement differences of about $\Delta s \cong 1{,}5$ to 9 mm. All these figures are ample evidence for the effectiveness of the PRF as a settlement reducer.

For monitoring of both the deformation in the ground and the contact pressure σ underneath the raft, three measuring locations (MS) were selected. Each location was equipped with a borehole for combined inclinometer and extensometer measurements and with a set of hydraulic pressure pads. The measuring locations were in the south-western area of the boiler house (MS1 and MS2) and in the western stair tower (MS3; ref. to Figure 10).

As an example, Figure 11 depicts the results of a mobile extensometer measurement at location MS1 which was carried out after placement of the raft. Graphed are the integrated deformations of the subsoil over the borehole depth of 20 m. Note that at the ground surface the settlement amounts to $s \cong 9$ mm. This compares reasonably well with geodetic measurements which, in equivalent part of the raft foundation, yielded settlements of about $s \cong 12$ mm (ref. to Figure 7).

Furthermore, the extensometer measurements gave evidence that the deformation of the ground is essentially controlled by the piles thus confirming the effectiveness of the piles as settlement reducers.

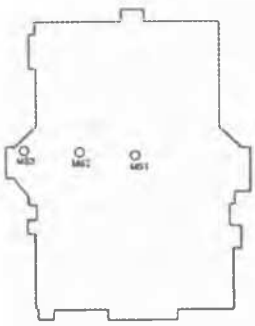


Figure 10. Measuring locations MS1 to MS3

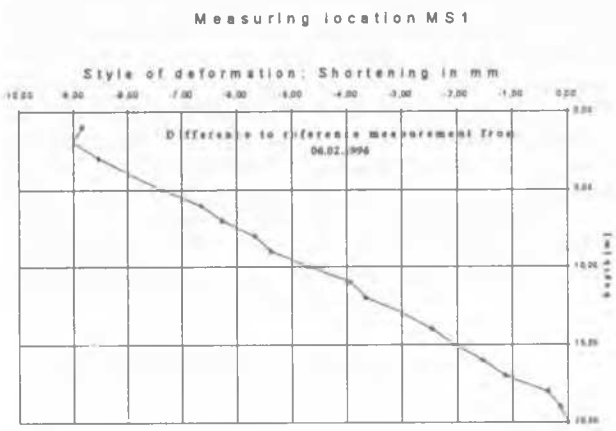


Figure 11. Integrated deformations as determined by mobile extensometer measurements in Borehole MS1

The horizontal ground displacement components, as monitored by inclinometer over the period from 02/1996 until 10/2000, turned out to be rather insignificant.

The monitored contact pressures were within the expected range, again confirming the fact that the majority of the loads were transferred via the piles into the ground. The portion of load which was directly transferred by the raft into the ground remained relatively low.

6 CONCLUSIONS

The total settlements of the PRF monitored after commissioning of the power station in October to December 2000 are in the order of 20 to 50 mm which is in very reasonable agreement with predicted values. The settlement differences of the boiler house foundation is $\Delta s < 10$ mm and thus within the limits tolerable. Based on various information, amongst them the results of the pile test trials (ref. to Figure 6), the consideration of the total loads of the buildings, the number and type of the piles selected and the results from settlement computations, it could be delineated that, in the project presented, the pile-raft coefficient α is of the order of $\alpha_{PRF} \cong 0.8$. This means that about 80 % of the total load is transferred into the ground by the piles with the remaining 20% by the raft via contact pressures at its base. With the selection of a PRF a significant reduction of the total settlements could be achieved which otherwise would have occurred with a more traditional raft foundation.

REFERENCES

Hanisch, J; Henning, R.; Jasch, E. and Klauke, E.W. 2000. Guidelines for the design and construction of piled raft foundation (in German). - Geotechnik, Vol. 23, No. 3, 198 - 205.

Katzenbach, R. 1993. The technical and economic significance of piled raft foundations demonstrated by means of high-rise buildings (in German). - Bautechnik, Vol. 70, No. 3, pp. 161 - 170.

Katzenbach, R.; Arslan, U.; Moormann, Ch. and Reul, O. 1997. Safety aspects in the design of piled raft foundations (in German). - Mitt. Inst. Versuchsanstalt Geotechnik TU Darmstadt, Vol. 37, pp. 143 - 151.

Katzenbach, R. and Moormann, Ch. 1998. Final Report of the research project on the "Develoment of design and safety concepts of piled raft foundations" (in German). - Phase 1, Deutsches Inst. für Bautechnik, Berlin.

Katzenbach, R.; Moormann, Ch. and Reul, O. 1999. Contribution to the load bearing capacity of piled raft foundations (PRF) (in German). - Pfahl Sympos., Mitt. Inst. Grundbau Bodenmech. TU Braunschweig, Vol. 60, pp. 261 - 299.

Lutz, B.; Wittmann, P.: El-Mossallamy, Y. and Katzenbach, R. 1996. The application of piled raft foundations - Design and experience in over-consolidated clay as judged by performance monitoring (in German).- Vorträge der Baugrundtagung DGGT, Berlin, pp. 153 - 164.

Placzek, D. and Jentzsch, E. 1997. Pile-raft-foundation under exceptional vertical loads - Bearing behaviour and settlements. - Proceed. 14th Int. Conf. Soil Mech. Found. Eng., Vol. 2, pp. 1115 - 1118.

Placzek, D. and Rothkegel, H. 1994. The concrete vibration pile - A modern kind of foundation. - Proceed. 13th Int. Conf. Soil Mech. Found. Eng., New Delhi, pp. 699 - 703.

Thaher, M. 1995. Practice-oriented simplified pre-dimensioning method for piled raft foundations (in German).- Proceed. Pfahl Sympos., TU Braunschweig, Vol. 48, pp. 23 - 49.