Performance of Foundations for Masts on Sand

Comportement des Fondations pour Pylônes

W. BLÜMEL Priv.-Doz. Dr.-Ing., Universität Hannover, FRG
F. LACKNER Ing. (grad.), BBC-Leitungsbau, Bauabteilung Hannover, FRG

SYNOPSIS Eight 352.5 m high guyed steel tube masts have been founded on mainly fine sand. The foundation design is described briefly. Settlement and inclination of the central base plates of 5 m square have been observed during and after mast construction. Some findings about time settlement behaviour, about variations of total settlement values related to subsoil conditions and about tilting of centrally and vertically loaded base plates are outlined.

INTRODUCTION

Settlements of foundations on sand normally take place rapidly with loading. An increasing part of the total settlement will be time dependent, if the sand is mainly fine and if the structure is subjected to load variations (BJERRUM, 1966). For certain buildings changes in load and oscillations induced by wind forces may affect the settlement behaviour.

For the eight masts discussed in this report only a very small inclination of the base plates is allowable after installation of sensitive porcelain insulators between the steel structure and the foundation. The maximum permissible value of 0.9 mm/m was set by the manufacturer of the insulators. That explains why the insulators were fixed after the masts were already resting on the base plates for some months. Extensive settlement measurements were executed and are still going on. This gives the opportunity to study the variations of the absolute and of the differential settlements of eight identical structures on quite similar ground, the rate of settlements related to the loading rate and the settlements after completion of mast construction.

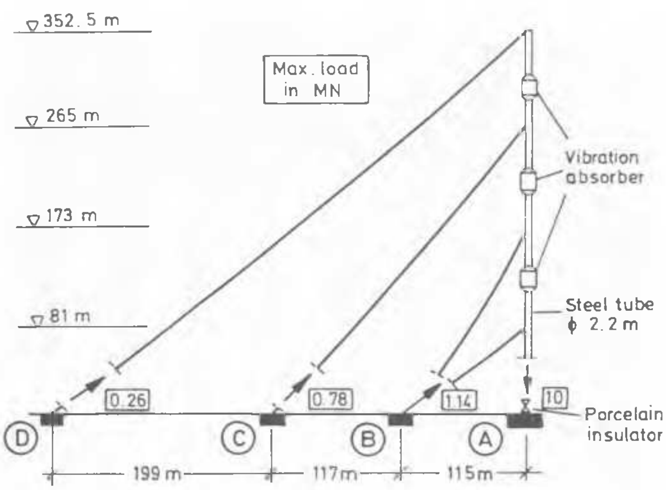

Fig. 1 Mast System and Foundation Load

DESIGN OF MAST FOUNDATION

The general layout of a mast is shown in Fig.1. Each mast consists of a steel tube, 350 m in height and 2.2 m in diameter, fixed by guy wires at four levels. At the mast top a wind velocity of 200 km/h had to be taken into account. For damping wind induced oscillations special vibration absorbers have been installed. The steel tube rests on a base plate of reinforced concrete, 5 m square and 1.3 m thick (Fig. 2 A). Between base plate and steel tube is a 2.5 m high porcelain insulator, which carries a max. load of nearly 10 MN. The horizontal load on the foundation is neglectibly small. To prevent any damage to the insulators due to eccentric loading, tilting of the base plate had to be limited as mentioned in the introduction. The guy wires are fixed to anchor founda-

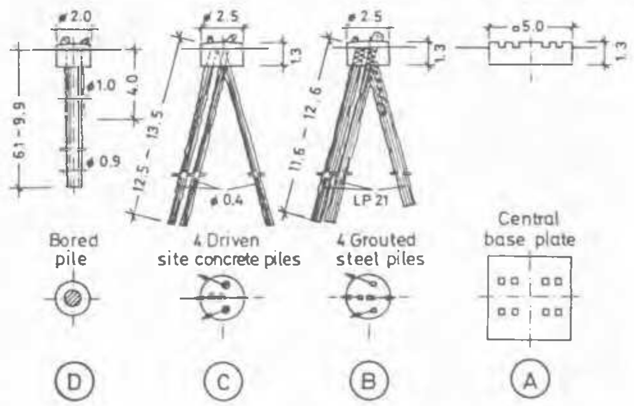

Fig. 2 Mast Foundation (Dimensions in m)

tions (B, C, D in Fig. 1 and 2), which are placed symmetrically on circles with diameters of 115, 232 and 431 m around the mast axis. For each mast 3 foundations of type B and C and 12 foundations of type D were constructed. Type D was required for electrical purposes. The various types of pile constructions used for the anchor foundations shown in Fig. 2 were found to be economical with regard to the different max. loads given in Fig. 1.

SUBSOIL INVESTIGATIONS AND SOIL IMPROVEMENT

The eight masts were erected in a moor area in Germany. The subsoil was investigated by borings, soundings and laboratory tests. Underneath a 1 to 4 m thick surface layer of peat mainly layers of fine to medium sand, locally containing some silt or organic matter, were found. Fig. 3 shows the profiles of the borings, executed in the centers of the eight masts. In Fig. 5 the grain size distributions of some representative samples are to be seen. The borings are marked in the same way as the masts by Nos. 11 to 14 and 21 to 24. For the central base plates of the masts and for foundations of further buildings the peat was removed and sand filled in hydraulically in a circular area of about 50 m in diameter. The density of the filling and of the sand layers underneath was investigated by static penetration tests (CPT). For clarity only the results of four tests near the center of mast No. 21 to 24 are plotted in Fig. 4. Similar results were found for the other masts. From the values of the static point resistance it can be concluded that the sand filling was rather loose whereas the undisturbed sand layers were in a medium dense to dense condition. To improve conditions for the mast foundation the subsoil below and around the central base plates was densified intensively by vibroflotation and adding of gravel down to 4 m below ground level. The sucess of vibroflotation work was controlled by static and dynamic penetration tests.

For settlement estimations oedometer tests with disturbed samples of the sand layers were performed. A floating ring of 7 cm in diameter and 3.5 cm in height was used. The stress-settlement and time-settlement curves are plotted in Fig.6. The variation of the oedometer test results

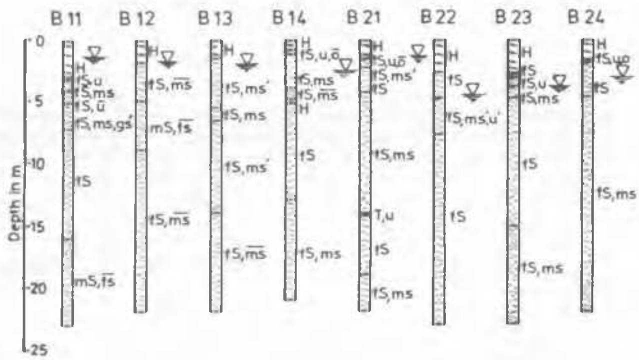

Fig. 3 Profiles of Borings

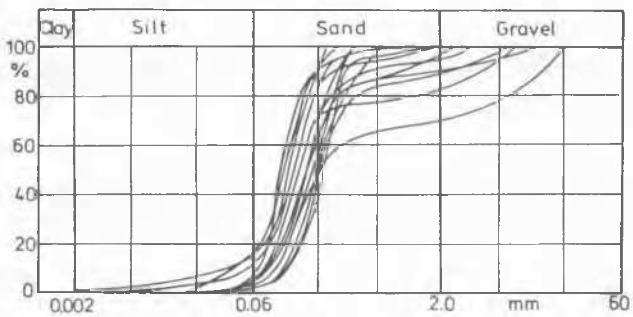

Fig. 5 Grain Size Distributions of Representative Samples

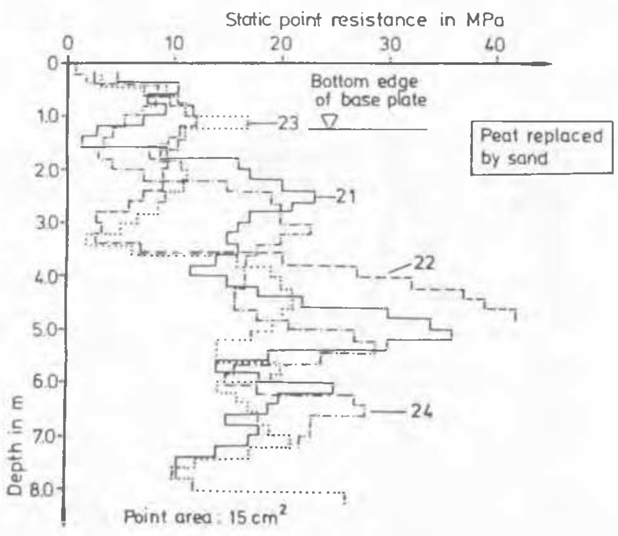

Fig. 4 Results of Static Penetration Tests (before Vibroflotation)

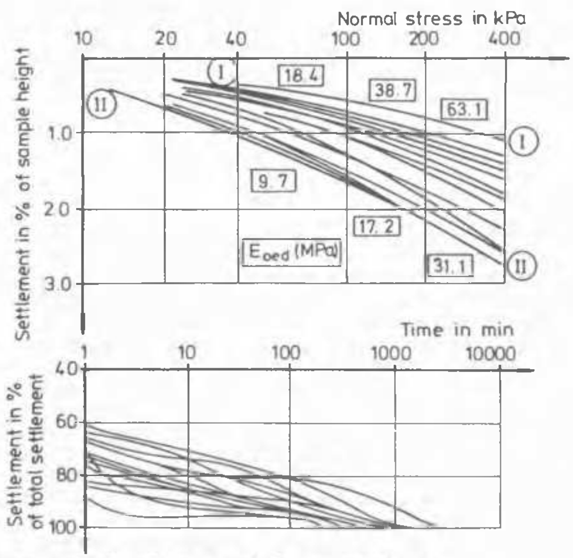

Fig. 6 Results of Oedometer Tests

seems to be mainly due to the variation in grain size distribution of the samples as shown in Fig. 5. For the boundary curves I-I and II-II in Fig. 6 the oedometric modulus E_{oed} was calculated and marked for the normal stress increments from 40 to 100, 100 to 200 and 200 to 400 kPa. Within each of these stress increments the minimum value of E_{oed} is approx. 50 % of the maximum value.

From the time-settlement curves measured for normal stress increments from 40 to 100 and 100 to 200 kPa, it can be generally seen that a certain time dependence of the settlements has to be considered. In this subsoil of mainly fine sand with some coarse silt the voids are already so small that the excess pore water pressure after loading dissipates gradually.

Based on the oedometer test results a very rough estimation of the time-settlement behaviour may lead to an instantly occuring settlement of about 75 % of the total settlement value.

SETTLEMENTS

For measuring settlements 4 galvanized steel bolts were installed near the corners of each reinforced concrete base plate. As fixed-points special piles were driven at a distance of about 20 m from the foundation center. Settlement observations started immediately after casting the base plate and were performed continuously during mast erection, prestressing of guy wires and are still going on after completion.

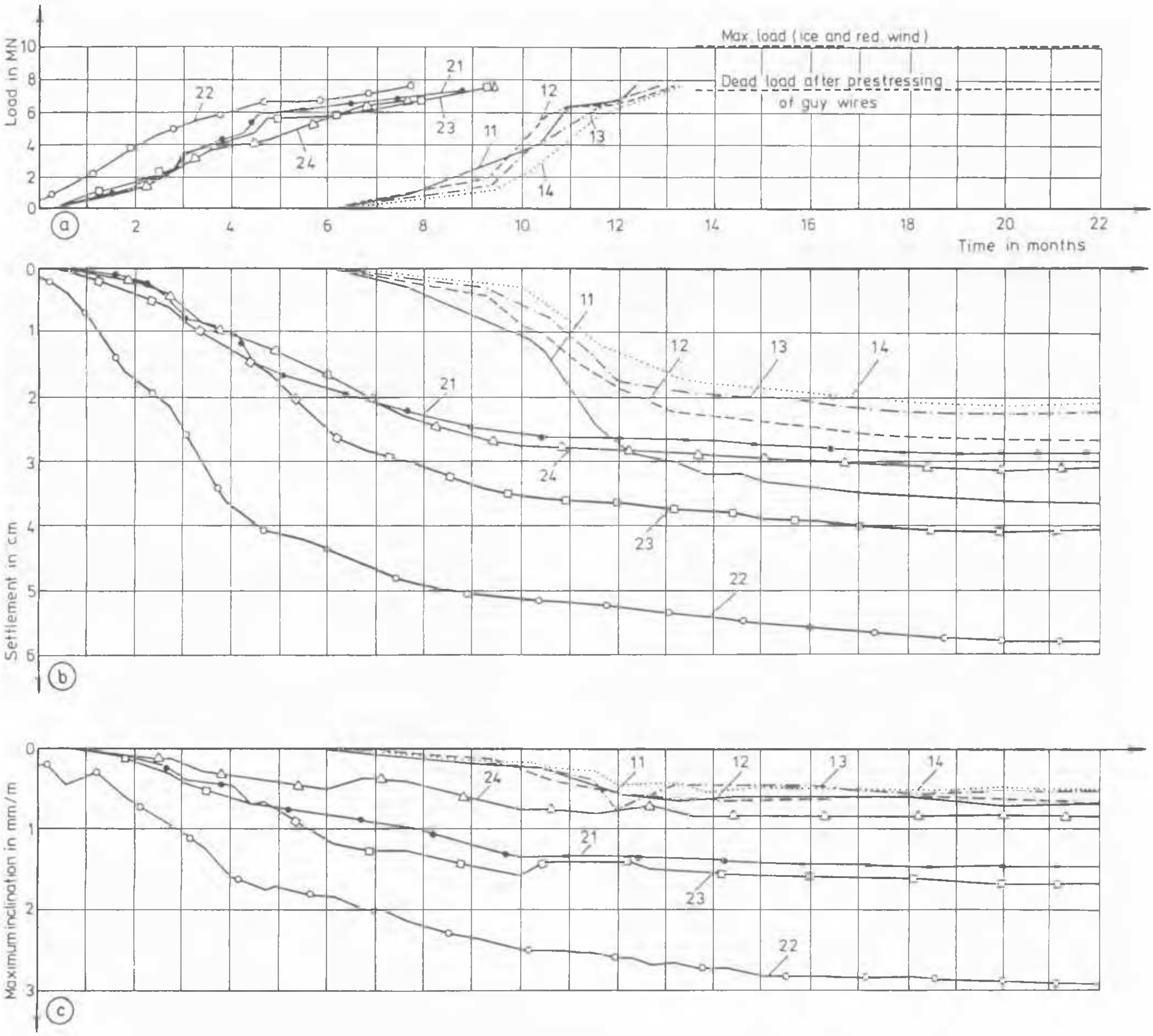

Fig. 7 Measured Settlements and Maximum Inclinations

The results are plotted in Fig. 7. In Fig. 7 a the foundation loads are shown as a function of time. The curve numbers denote different masts. The masts were installed in two groups of four with a time lag of about 6 months due to technical reasons. The installation time of one mast took about 6 to 9 months. The dead load of the structure acting on the central base plate after prestressing of guy wires is 7.6 MN, whereas the maximum load is~10 MN, caused by max. ice load and reduced wind load according to German standards. The max. load leads to an additional pressure on soil of approx. 400 kPa. The weight of the base plate is largely compensated by relief due to excavation.

According to the load-time curves in Fig. 7 a all foundations were loaded at almost similar rates, but great differences were observed for the settlements. In Fig. 7b the average values of the settlements of the four bolts are plotted for each mast foundation. About one year after completion of the structures the average settlements for 7 masts are in the range of 2 to 4 cm, whereas mast no. 22 has already reached a value of nearly 6 cm. Most probably certain variations in the subsoil,also caused by replacement of the peat, seem to be responsible for the differences in settlement behaviour. The max. inclination of the base plates has been calculated from the measured settlements and the results are shown in Fig. 7c. For the 8 base plates the max. inclination varies between 0.5 and 3 mm/m. The porcelain insulators were installed between the 13th and 15 th month. This late installation was necessary with regard to the allowable max. inclination of 0.9 mm/m of the insulators.

For comparison with settlement calculations load-settlement curves, based on the measured values, were plotted for each foundation in Fig. 8. The max. average settlements of the period examined were related to the max. load of~10 MN.

Settlements of the base plates at the locations of the bolts were calculated using the stress relations given by the boundary curves I-I and II-II in Fig. 6 for the sand layers deeper than 4 m below ground surface. For the zone densified by vibroflotation a constant oedometric modulus of 100 MPa was taken into account. The stress changes in soil induced by the foundation load were analysed by Boussinesq's theory with modifications by Fröhlich (1934). The results are marked by the thick lines I and II in Fig. 8. The measured load-settlement curves are to be expected between these two lines. Greater deviations are found only for mast no. 22.

Max. rates of settlement ranged from 0.5 to 1 cm/month. After completion of construction an almost constant settlement rate of about 0.5 to 1 mm/month was measured for several months. A certain reduction of this rate was found during the last three months of the observation period as shown in Fig. 7 for all foundations, although the two groups of masts were completed at different times. Between completion of each structure and the end of month 22, the increase of the average settlements is approx. 20 % of the total values. The settlement observations are still going on and a certain increase of the settlements is expected.

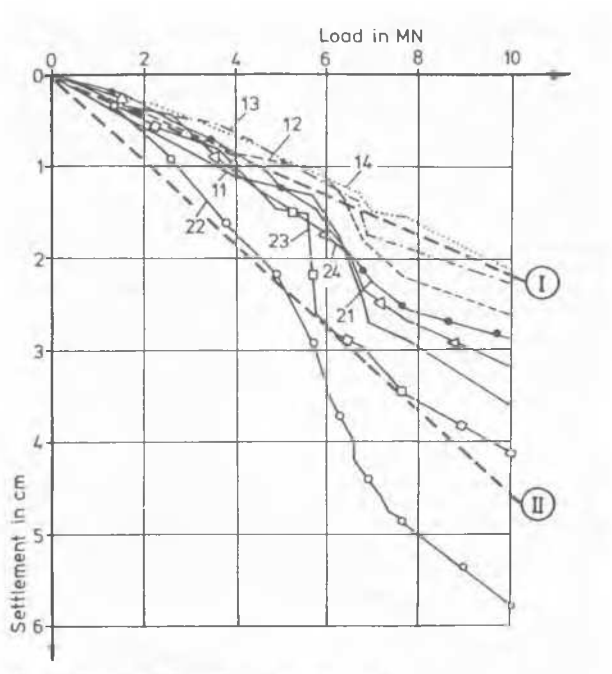

Fig. 8 Load-Settlement Curves

CONCLUSIONS

1. Base plates of 5 m square and 1.3 m thick for guyed masts on fine sand show a certain amount of time dependent settlements after completion of construction, caused by consolidation of the fine sand and by wind induced oscillations of the structure. For the observation period discussed herein the amount of these settlements is about 20 % of the total settlements.
2. The variation of the total settlements is greater than expected from the results of subsoil investigations. For 8 identical structures on fairly similar subsoil total settlements between approx. 2 and 6 cm were observed, whereas calculations based on extreme values of the laboratory test results range between 2 and 4.5 cm.
3. Base plates are tilting, although the load is acting centrally and vertically and no remarkable variations in subsoil conditions are found within the foundation area of 25 m². Max. inclinations between 0.5 an 3 mm/m have been measured.

REFERENCES

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