In the design of foundations for large buildings on deep deposit of cohesive soils it is generally seen that if raft foundation be chosen the foundation will have sufficient factor of safety against shear failure but corresponding settlement will be very high to permit. In such cases pile foundations are generally selected causing very large cost for such foundations. The settlements are successfully controlled in such foundations. However in the late, it has been recognized if few number of piles are installed at suitable locations below the raft foundation for such structures, the resultant settlement under such structures will be much smaller and will be within permissible limits compared to that below the raft without provision of piles. Use of raft in conjunction with some piles will be costlier than in case where only raft is used if possible but much less than the case when only piles are used. As a result in

Due to increasing economic development, rapid industrialization and decreasing availability of land for construction in thickly populated countries like India, scope for extending construction in horizontal direction is becoming increasingly lesser resulting in construction of high-rise building with increasing number of floors. In such cases if raft foundations are proposed it is generally observed allowable bearing capacity of such rafts are quite high so that such foundation can withstand the applied loads due to high-rise buildings to a great extent without causing shear failure but the major problem of such foundation is that the total settlement below the foundation at different locations will be very high beyond permissible limits.

Foundation for High Rise Buildings

MB Bureau
The past decades there has been increasing recognition to use some piles with raft to reduce the total and differential settlement of raft leading to considerable economy without compromising the safety and performance of the foundation structure system. Such a foundation system is called piled-raft. One of the most important buildings constructed with such system is for the foundation system of the world’s tallest building the Burj Dubai. Similar foundations are also being adopted in India for twelve storey buildings in Chennai. The adoption of piled-raft foundation for high-rise buildings is also very common in European cities. Thus it seems on the context of increasing construction of buildings of large heights in metropolis in India and other countries, piled-raft foundation will be increasingly adopted as a most economic safe foundation system. In this paper an attempt has been made to describe the concept of load transfer mechanism for piled-raft foundation from superstructure to the foundation.

The present paper is on customary foundation systems for high-rise buildings such as raft and pile foundation as well as the innovative foundation system of combined pile-raft-foundation. Where piles are primarily used to reduce settlements and where an adequate factor of safety against failure is provided, the innovative combined pile-raft foundation (CPRF) has been put forward in the past. Some case study of few high rise buildings is included for better understanding.

**Foundation systems**

Every design will have to satisfy the following conditions-

- The factor of safety against failure of the foundation and of the supporting soil has to be adequate => ultimate limit state (ULS)
- The settlement of the foundation as a whole and in particular differential settlements under working load should not be so large as to affect the serviceability of the structure => serviceability limit state (SLS)
- The safety and stability of nearby buildings and services must not be put at risk => ultimate limit state (ULS) / serviceability limit state (SLS)

The three common types of foundation system that are adopted for High-Rise buildings are-

- Raft Foundation
- Pile Foundation
- Combined Pile-Raft-Foundation (CPRF)

With increasing height of building respectively increasing loads the depicted raft foundation is not suitable to transfer the loads properly into the ground. Therefore a pile foundation is often used. The main function of a pile foundation is to transfer all loads with piles to lower levels of the ground which are capable of sustaining the load with an adequate factor of safety (ULS). The innovative combined pile-raft-foundation (CPRF) is nowadays often used to transfer the loads into the ground. In comparison to a pile foundation, the combined pile-raft foundation both the piles and the raft transfer the loads into ground. The loads are transferred by skin friction and end bearing as well as contact pressures of the raft foundation (bearing pressure) (See in Figure 1).

![Piled Raft Foundation: Burj, Dubai](image)

The piles are used up to their ultimate bearing capacity (load level) which is higher than the permissible design value for a comparable single pile. The combined pile-raft-foundation represents a complex foundation system, which requires a qualified understanding of the soil-structure interactions.

The foundations system of the CPRF can lead to the following advantages in comparison to a raft or pile foundation:

- Reduction of settlements and differential settlements of structures.
- Reduction of tilt in consideration of eccentric loading or inhomogeneous soil conditions.
- In case of hybrid foundation it is possible to avoid joints in the raft.
- Reduction of number of piles and pile length in comparison to a pile foundation.

![Figure 1: Load Transfer Mechanism in Combined Pile-Raft-Foundation](image)
- Reduction of forces, stresses within the raft in case of an optimal position of the piles.

Due to the complexity of this foundation system no valid calculation method has yet been implemented in national or international technical codes and standards. Recommendations exist though for CPRF. Therefore the combined pile-raft-foundation must be monitored by means of the observational method with a monitoring programme.

Case studies

- Main Tower – Frankfurt, Germany

The building reaches a height of 200 m. The building is founded on a combined pile-raft foundation. The thickness of the raft within the tower is between 3 to 3.8 m. A total of 112 piles with diameter of 1.5 m were installed. The length of the piles varies from 20 m to 30 m (Figure 2).

The ground encountered consists of quaternary sands down to 10 m below the surface where it is underlain by tertiary sediments of the Hydrobien. These sediments (Frankfurt clay) consist of clay interbedded with sands and limestone bands (Figure 2). The ground layers of the Inflaten (Frankfurt limestone) and Certithien (marl) were encountered beneath the Hydrobien.

To ensure an economic design of the Main Tower three innovative ideas were put forward:

1. The bored piles of the retaining wall are part of the foundation system (combined pile-raft foundation). They transfer the loads in addition to the 112 foundation piles into the ground. Figure 3 shows the position of the piles of the foundation and of the retaining wall.

2. The building pit and the first floors of the main tower were constructed in top-down-technique to reduce construction time and to provide a pit which observes stability and serviceability of neighboring structure. By using this technique it is possible to construct the basement floors and the upper floors at the same time (Figure 3).

3. Apart from their static function the piles of the foundations and partly of the retaining wall are used for the environmental-friendly heating and cooling of the building. For this, the piles were additionally installed with heat exchanger tubes (Figure 4), so that the piles work as heat exchanging elements to create a closed system. Energy is transferred to the ground from the exterior (outside air) and stored until it is needed (Figure 4). The energy piles can load and unload the seasonal storage. In winter energy can be withdrawn, thus a cooling of the ground arises. In summer the cooled down ground can be used for cooling the building through the ceilings.
For this, a very low groundwater velocity is essential. The monitoring shows that the foundation piles of the Main Tower carry approx. 37% of the total load of the building whereas the piles of the retaining wall carry approx. 26%.

- Sony Center – Berlin, Germany

The building reaches a height of 103 m. The building was constructed directly next to an existing railway station. The geometrical position of the high-rise building on the overall area of the raft causes a large eccentricity of the loads (Figure 5). Due to this fact as well as the geological conditions a combined pile-raft foundation was constructed to transfer the loads into the ground. The thickness of the raft within varies between 1.5 and 2.5 m. A total of 44 bored piles with diameter of 1.5 m were installed.

- QIPCO Tower - Doha, Qatar

The QIPCO Tower is situated at the coastline of the West Bay in Doha, Qatar. The building reaches a height of 200 m (Figure 6). A ground investigation is currently in progress, which has been planned by the authors. It consists of drillings, geophysical methods, field and laboratory tests are the basis for a successful planning and construction of such a structure. The combination of different investigation methods makes it possible to detect relevant geological conditions such as the phenomena of cavities. This innovative application of geophysical methods offers the possibility to screen the ground three-dimensionally in the affected zone. This method in combination with drillings can offer savings in both time and costs. The qualified interpretation of all obtained data serves as a basis for the numerical simulations to design an optimised foundation system as well as to evaluate all necessary design parameters for the structural engineer. For the transfer of the loads into the ground, a combined pile-raft foundation for the tower area is in planning.

- The Commerzbank, Frankfurt Germany (Pile Foundation)

The building is founded on a pile foundation. The building was constructed directly next to an existing high-rise building. The existing building reaches a height of 103 m and is founded on a raft. A total of 111 telescopic piles with diameter of 1.8 m within the first 20 m beneath the

The ground and groundwater conditions were explored by boreholes. Up to a depth of 4m beneath the surface fillings and organic soils were encountered underlying by loose to medium dense sands of the Pleistocene. Dense sands were encountered in depth beyond 15 m. A layer of boulder clay with a thickness of 5 - 10 m was found. For the verification of the carrying behaviour of the combined pile-raft foundation a monitoring programme was installed. A total of 4 piles are instrumented with measuring devices, such as pressure cells at the top and bottom as well as strain gauges within the piles. Beneath the raft a total of 5 earth pressure cells were installed. Additionally 13. The settlements of the building are monitored by geodetical points. The maximum settlement of the building add up to 2.8 cm. The tilting is smaller than 1/2000. These results cause no negative effect on the serviceability of the building. The measured mean value of pile resistance was measured to 15 MN for piles for a centre pile.
raft, followed by a diameter of 1.5 m were installed. All piles were constructed with a jet grouted shaft as well as jet grouting 10 m underneath the piles in the cavernous limestone.

The maximum settlements of the building add up to 2.1 cm. The minimum settlements were encountered with 1.5 cm. This leads to a tilting of smaller than 1/2000. These results cause no negative effect on the serviceability of the building. The monitoring shows that the 111 piles of the Commerzbank carry approx. 96 % of the total load of the building. This indicates that not all loads are transferred by the piles into the ground.

Conclusion

On the basis of an extensive ground investigation and a detailed description of the ground, the foundation of high-rise buildings can be planned in an economic and safe manner. The report shows customary foundation systems for high-rise buildings such as a pile foundation as well as the innovative combined pile-raft-foundation. The choice of the adequate system is often depending on the proof of the serviceability of the high-rise building and / or neighbouring structures. Pile foundations have been constructed to reduce the settlements and to satisfy the ultimate limit state and what is more the serviceability. For the design of a pile foundation it is often required that each pile must individually satisfy an according factor of safety. If a pile foundation is just designed to reduce settlements, the required and known geotechnical proofs are a conservative design approach.

Where piles are primarily used to reduce settlements and where an adequate factor of safety against failure is provided, the innovative combined pile-raft-foundation (CPRF) has been put forward in the past. The essence of the combined pile-raft-foundation is to employ piles so that settlements are reduced to an acceptable amount. The successful design and construction has been verified by many structures including many high-rise buildings. For an even more efficient use of foundation piles, the use of geothermal energy with help of these piles has been lately carried out. For this, the foundation piles have been additionally equipped with heat exchanger tubes to use the ground as an seasonal storage. Many more applications to use geothermal energy are possible. More effort should be put into this field of geothermal foundation system to provide and improve new possible innovative ideas for an environmental-friendly use of energy.

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