Proposals of Application of System of Combined Foundation for Buildings Located in Earthquake Areas and in Sea Bays

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Abstract: This paper presents description of system of the combined foundation, which is a unique structural solution invented for needs of construction of heavily loaded buildings located on the subsoil of very small load carrying ability, for objects placed in the mining damage sectors or planned to be constructed on another type of unstable ground. Basic laws of theory of structures together with shapes of certain biological forms existing in the nature were the inspirations for working out of the system of combined foundation. The system consists in general of two groups of structural components, while the first one is created e.g. by the reinforced-concrete beams or boxes laying directly on the background, the second one is constituted by intermediate structures suitably connected with the first group by means of nodes uniformly distributed along the neutral axes of e.g. the basic beams. The surface of the system of combined foundation is theoretically unlimited, what implies that even the extremely heavily loaded buildings can be erected on subsoil of extremely small load capacity. The structural system can be especially useful for buildings located in seismic areas. In the paper there are presented examples of propositions of various buildings being planned to erect on different backgrounds including the tall building situated in the sea bay.

Keywords: Foundation system; Load capacity of ground; Structural system; Combined structure; Tall building; Earthquake area; Mining damage sector; Sea bay

1. Introduction

Very difficult problem of safe location of each type of building on a weak subsoil or on an unstable terrain situated in seismic areas belongs to the always actual challenges for each generation of architects and engineers. Typical systems of foundations mostly used nowadays are presented in numerous books, papers or reports, described among others in [1,2]. There are numerous and very complex requirements and technical conditions, which have to be fulfilled by the desirable types of the foundation systems, successful applications of which are described on selected examples of technical solutions in works [3,4,5]. Tall buildings belong to the group of heavily loaded objects. Small load carrying ability of the subsoil makes hard the processes of construction of such buildings located there, what mostly forces to apply the deep and expensive pile foundation systems. Range of difficulties considerably increases when the building has to be placed in the seismic areas as well as in the lake or sea zones.

2. Formulation of Structural Problem

Safety is the most important feature of the bearing structural system of the building and especially of its foundation under acting of extremely big values of horizontally and vertically loads. The foundation should provide the stable position for the building even during the biggest earthquakes and after large casual translocations of the ground beneath the building foundation. The required foundation structure should make possible to locate the heavily

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loaded buildings on the grounds of extremely small load carrying ability without necessity of application of the deep foundation pile systems, which are expensive and which usually constitute a severe interference in the underground water system. It will be advantageous if the foundation system will also make possible the safe construction of buildings, which have to be located on the water, in the lake or sea areas.

3. Structural Concept of the System of Combined Foundation

 Appropriately large surface of the foundation may guarantee that the stress value in ground will not exceed permissible value of the subsoil load ability. Increasing the foundation surface has to be made with respecting the basic rules of theory of structures. This remark refers in particular to enlarging the span of cantilever components of the foundation structure. Suitably stiff or resistant and economic structural solutions one can observe in world of nature like for instance the form of the tree root system shown in Fig. 1a. Another inspiration during the design process were patterns of the main stresses in the free-ends beam presented in Fig. 1b.

![Fig. 1. Patterns of structural configurations being inspirations during the design process and general schemes of the structural concept of system of the combined foundation](image)

The point of this structural system is to transmit the outside big force $F_v$, see Fig. 1c-e, by means of suitable nodes of an intermediate structure to the matter of basic components shaped in form of e.g. beams (1) located on a common horizontal slab (2) and also connected by distance members (3). The load force $F_v$ is applied to the upper node A of a short strut AB, which is inserted tightly inside appropriate guides and which has only one degree of freedom along the vertical direction. To the lower node B of this short vertical strut is jointed to the intermediate structural system composed of two independent parts. Scheme of its upper part (4) is shown in Fig. 1c and scheme of its lower part (5) presents Fig. 1d. Patterns of both parts are symmetrical towards the horizontal central axis of a beam, where moreover are placed nodes connecting these parts to the main bodies of the beams. These central nodes are uniformly distributed along the beam’s central axis, due to which the force $F_v$ can be also uniformly distributed along the whole beam (1), except the boundary node, where the big reaction $V_4$ is directed down. After combining both parts the horizontal components of reactions $H_4$ and $H_5$, see Fig. 1c and Fig. 1d, are mutual wiped out because shapes of both parts of the intermediate system are symmetrical towards the horizontal central axis, see Fig. 1e. Final lenticular shape of the intermediate system can be put in the narrow space between two parallel beams, see Fig. 1f, or it can be suitably arranged around the body of a single beam, see Fig. 1g. Schemes shown in Fig. 1c-g present the repeatable part of the proposed system and can be considered as the module of this structural system. Basic components of system of the combined foundation, represented in this case by horizontal beams, can take various and different forms, what describes work [6]. The same remarks refer also to the shapes of the intermediate system. Some examples of basic structural configurations of the intermediate system are shown in Fig. 2.
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From analysis of schemes presented in Fig. 1c-e follows that system of the combined foundation can be used for specific purposes, for instance as the support structure of objects, which are loaded in an eccentric way. Because of practical reasons the system will be mostly applied in form of the symmetrical location of structural modules or units towards the position of the point of applying the vertical load (Fv), see Fig. 2. One should remember that nodes A and B of the short vertical strut are not connected to the main matter of the horizontal beams (1). Number of central nodes (G), including boundary nodes (CB), in structural configuration of the intermediate system shown in Fig. 2a, is theoretically optional. Geometry of this system is determined by general rules of shaping of the arch and funicular structures. Stability of the considered configuration is sufficient, it can be significantly increased by application of a suitable truss system but in this case the uniform distribution of intermediate vertical reactions will be significantly destroyed. Topological features of the proposed structural system cause, that it has inherent ability to absorb a certain amount of the vibration energy evoked by the dynamic loads and generated by e.g. by earthquake. This ability can be enhanced by suitable arrangement of hydraulic jacks (Dp), see Fig. 2a-c, which will play role of the vibration dampers. The bearing structure of the aboveground floors of the building can be supported on the combined foundation in the way presented in Fig. 2c. Because in the boundary nodes (CB) are acting big vertical components of reactions, in this case directed down, therefore it is suggested to put additional foundation piles (Fp) directly below these nodes. Moreover stability of the boundary zones of the combined foundation can be ensured by suitable design extreme walls and slabs forming a kind of scoop loaded by the ground situated inside of the soil wedge (Sw), see Fig. 2c. Columns of a multi-storey building can be supported also in suitable nodes of the single unit of the intermediate system represented in Fig. 2c by nodes G1, G2 and G3.

Modular parts of the foundation, determined by geometric sizes of lenticular units of the intermediate system, can be repeated several times along horizontal direction. Structural features of this technical solution cause that the number of possible reproductions is theoretically unlimited. The adjacent units have to be connected together by means of central nodes of the type "N", positions of which are indicated in Fig. 3a-c by localizations of node N, node N1 and node N2. This group of central nodes has to be not connected to matter of the foundation beams. All nodes...
belonging to this group are of two degrees of freedom onto the vertical plane. If the modular units are repeated twice then in boundary central nodes (CB) act vertical components of reactions directed typically, it means directed up. But in this case central nodes (C) of the boundary units are subjected to acting of vertical reactions directed down, therefore stability of this part may be increased e.g. by putting additional foundation piles (Fp) right below these nodes, see Fig. 3a-b. As it was mentioned previously the significant part of energy caused by seismic vibrations can be absorbed by the special technical devices made in form of e.g. computer controlled hydraulic jacks (Dp), see Fig. 3a-c, and arranged in selected parts of the intermediate structural system. If in seismic area the building foundation has to be deeply located into the ground, see Fig. 3b, a special buffer vertical zone (Bf) should be constructed in boundary part and moreover the whole foundation system should be horizontally separated (Hsep) from the subsoil. Intermediate system can be supplemented by additional triangular sets of members represented by set A1B1N1 and set A2B2N3, see Fig. 3d. All nodes of this triangular set have to be not connected to the main bodies of the horizontal foundation beams. If structural scheme of the aboveground part of the tall building will have form presented in Fig. 3d, then the structural system of the whole object, including the foundation structure, is called the combined structural system [7,8] and its shape can be subjected to numerous further transformations carried out in order to receive the more efficient structural solutions.

Fig. 4. Examples of possible forms of system of the combined foundation and locations of buildings supported on it

The proposed structural system of the combined foundation can be built by means of appropriate reinforced concrete boxes created by means of various types of modular units (Im), see Fig. 4. Surface of this foundation structure can be very large, if fact it is theoretically unlimited, and the structure can take regular shape, see Fig. 4a, or it can be of an irregular form, see Fig. 4b.

4. Examples of Possible Applications of the Proposed Structural System

System of the combined foundation can be the safe and economic efficient base for various types of buildings located in areas of the very difficult ground conditions, what is presented on examples of two selected conceptual projects. The first one is the design of the building complex called the GeoDome Sky Towers, see Fig. 5, prepared for the international architectonic competition eVolo2012; author: Janusz Rębielak, technical cooperation: Maciej Smoliński. The designed complex is located in an urban area of city Wroclaw, in Poland and it is also presented in paper [8]. The four main vertical buildings and the broad horizontal building of the basis are designed according to the rules of the combined structural system. It consists of four tower buildings having form of rectangular prisms containing 80 storeys each. These towers have square form of the base projection and they are put on a common broad basis of similar form having dimensions 252,00 meters x 252,00 meters and containing three aboveground service storeys. The main four towers are connected together by means of specific spatial structures having form of huge arches situated vertically and running from the half of the tower’s height to the suitably selected lower and upper parts of these corresponding towers. In the base projection central axes of these arches run along diagonals of the square basis of the whole complex. Moreover these four main buildings are connected together by means of a central building having form of geodesic sphere, which joints each tower in its half. The outside shell of this sphere is designed as geodesic structure. The designed complex of GeoDome Sky Towers is founded almost directly on the subsoil surface, what enables application of the combined structural system. The surface of the ground floor is 0,45 m above the terrain level. Modular boxes of the foundation are placed on beam-and-slab plate of construction depth of 1,75 m. The modular unit of the complex equals 36,00 meters what corresponds to the length of single side of
square base of one of the main towers. Spaces of these buildings is devoted for various types of offices, hotels, apartments and for similar others useful purposes. On the top building is located additional technical storey. Total height of each tower equals 382.95 m. The four main tall buildings are supported on the structure of the combined foundation of the structural depth of 18.00 meters. Its inner space is horizontally divided into three storeys, each of the structural height of 6.00 meters. The ground storey is devoted mainly for the needs of car parking and for some technical compartments. Area of this part is suitably separated from the space of the commercial and service rooms located along the perimeter of the whole complex. In the marked spaces of the huge spatial arches are designed zones of the green gardens resembling various types of world’s forests, which are accessible for all user of this complex. In its centre is located a big geodesic sphere of diameter equals 100 meters. The sphere is joined by means of big corner nodes to the structures of each tower. These nodes are located on the level of the half of the height of all towers and on the middle level of the geodesic sphere. On this level is possible the direct communication between spaces of all components of the building complex. The upper part of the geodesic sphere plays recreation role and it is aimed as a leisure centre designed in form of tropical island with large pool, sand beach and numerous other facilities. The tropical island is supported on huge spatial structure located below having form of pyramid directed upside down. In its inner space are placed technical and service storeys including four auditorium halls separated by sliding walls, which can constitute one big auditorium having foldable stands, what will make easy to transform it into a multipurpose hall. Moreover in the lower hemisphere there are planned numerous other conferences and exhibition halls, sport and fitness halls and other rooms of various useful purposes.

Fig. 5. Perspective views of the designed multi-purpose complex named GeoDome Sky Towers

When particular components parts will be constructed as the waterproof boxes then the system of combined foundation (SCF) will have a huge uplift pressure. That is why it may be considered as a kind of an artificial floating island and it could be base for a building (Bld) placed there, see Fig. 6. The whole floating structure will have possibility to move only along the vertical direction according to the current level of the water. Horizontal movements will be eliminated by help of a set of immensely heavy and rigid plies (Pls) being the fix anchorage for that complex. In the narrow vertical space (Ns) will be arranged technical devices making possible the smooth and unobstructed vertical movements of the floating base (SCF).

Fig. 6. Simplified vertical cross-section of a multi-storey building located on floating type of combined foundation

The second conceptual project of Floating Bay Tower, see Fig. 7, has been prepared for the international architectonic competition eVolo2015; the author: Janusz Rębielak, technical cooperation: Wojciech Ciepłucha and
Maciej Rębielak [9]. This solution is suggested for heavy loaded buildings within coastal and bay areas, as well as within areas surrounded by piers and breakwaters that limit non-uniform and sudden sea level rises. This is important especially during tsunamis, which result in to high sea levels during the highest ebb tide possible. Floating Bay as a multipurpose structure is created by a set of three separate buildings, each with the shape of an elongated octahedron and based on an equilateral triangle with side length of 30 meters. Each of the buildings is designed by structural system called famed polyhedron and can house a maximum of 36 typical storey of approximate height of 4.16 meters. The total height of this complex, above the level of its foundation, is 158.32 meters. The complex of Floating Bay Tower is mounted to appropriate structural nods of the combined foundation, whose base is shaped around a hexagon with segments that are also formed into equilateral triangles, each with a side length of 30 meters. The structure height of the floating foundation reaches 18 meters, while the total draft should not exceed 10 meters. Massive reinforced concrete pillars, with side length slightly smaller than 30 meters, are mainly filled with massive rock material and prevent horizontal movements. The floating foundation can move vertically only, depending on the current sea level. Accessing Floating Bay Tower is possible from land by means of two small bridges. From the sea-side the complex is protected by a structure, located 150 meters away, properly mounted and floating mainly below the water level. The structure is made of massive, vertical pillars and breakwaters, which are created using a specific type of the sponge space structure. Numerical models of the bearing structures of all these designed objects were defined in programming language Formian [10].

Fig. 7. General views of the Floating Bay Tower

5. Conclusions

The proposed system of combined foundation enables construction the very heavily loaded objects on subsoil of extremely small load carrying capacity. It is possible due the uniform way of distribution of reaction forces along the large foundation surface, which horizontal dimensions are theoretically unlimited. In these cases even a large displacement of ground beneath the foundation will have scant influence on stability of the supported building. Application of this structural system does not need to prepare deep trenches, what implies that costs of this type of foundation can be relatively low. It means also that the underground water system can be untouched. Structural features cause that the combined foundation has significant features of a specific type of the passive vibration damper. Features of effective absorbing the vibration energy will be significantly enhanced due to the appropriate arrangement of e.g. computer controlled hydraulic jacks. With this equipment the system of combined foundation can also be applied to straighten buildings being previously inclined. The system of combined foundation has to be subjected to numerous and comprehensive analyses in order to confirm and verify all the assumptions.

References
