# Structural concept of system of combined foundation designed for buildings located in earthquake areas

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## Abstract

The paper presents initial structural and static analyses of an innovative type of foundation structure, which can obtain theoretically unlimited horizontal surface. This implies that the proposed system of combined foundation can be applied for construction of heavily loaded buildings located on subsoil of very small load carrying ability. Basic rules of theory of structures, like e.g. the principle of superposition, are respected during process of design of the proposed structural system. Important inspiration in this process have played patterns of stress trajectories in the free-end-beam as well as the concept of Michell's beam. The inner build of the system of combined foundation makes possible the very uniform distribution of the load forces onto its horizontal surface. Moreover this system has inherent structural features of a damper, due to which it is able to absorb safely a significant part of energy of vibrations evoked by earthquakes. Suitable application of the proposed system makes possible to design safe structures of high-rise building located in earthquake areas.

**Keywords:** Foundation, Building structure, Subsoil, Load capacity, Earthquake, Tall building.

## Introduction

Structural system of a building, together with its foundation, has to be designed according basic rules of theory of structures and application of modern theories [1,2,3]. Safety problems of structural systems of buildings located on ground of small loading ability or in earthquake areas belong to the constantly actual research tasks in engineering [4-7], likewise aspects of damping of the energy vibrations caused by the earthquake and accidental land's slides or casual displacement of a ground beneath the foundation structure [8-11]. In case of tall buildings their bearing systems should provide them with suitable rigidity and stability defined by buildings codes mostly under the wind load. Tall buildings, as well as all types of buildings, are time to time subjected to act of huge values of dynamic loads. Bearing systems of such objects have to at the same time of two contradictory structural features; on the one hand they have to be very stiff but on the other hand they have to be flexible to some degree [12-14]. Some similar remarks refer also to the foundation systems, while structural problems to be solved are very complex. There are numerous structural systems of foundation applied in the practice for a long time, which are permanently modified and gradually improved. They may be subdivided generally into two main groups of the shallow and the deep foundation systems. Systems of the shallow foundations are mostly applied when the passive earth pressure beneath the bottom surface of the foundation is also within the range of load carrying ability of the ground and they are usually not complex because of simplicity of their structural forms. Complexity of the deep foundations makes them often difficult to construct that is why they are the very expensive technical solutions.

## Definition of expected structural features of foundation system

Systems of deep foundations are complex, they need a long time to be constructed, they are expensive technical solutions and their applications may have serious impact onto the environment. Thus it seems to be more convenient to apply one of shallow types of the foundation systems but application of this concept is in certain cases also not easy. The requested foundation has to be of considerable big horizontal surface or length (L1), see Fig. 1a, while the clear span of cantilever part of the foundation structure (Ks) is strictly limited by its mutual relationship to the construction depth (Fd), what indirectly is determined by permissible deflection of the cantilever structure. Surface of the foundation may be significantly enlarged in simple way by increasing of its horizontal dimensions along two orthogonal directions, due to which value of passive earth pressure could be significantly smaller than in the typical configuration of the shallow foundation placed beneath the ground floor of a building. Expected shape of the widely spread foundation should be characterized by big stability under acting of complex set of big loads, including vertical load (G), sometimes huge horizontal load caused by wind (W), see Fig. 1a. and also under acting of forces caused by rapid dislocation of subsoil along its parameter (Gd) or e.g. evoked by displacement of ground beneath even a vast part of foundation area (Gd2) of the foundation. New structural system should provide the foundation with very large horizontal surface, while its structural depth has to be relatively very small. Structural task defined in this way is very difficult to solve because the searched technical solution has to fulfil at the same time some contradictory structural requirements, which have been shortly discussed above. In processes of solving such complex tasks, there are mostly very helpful conclusions following from analyses of structures existing in the nature as well as the suitable application of basic rules and theorems of theory of structures referring to stress trajectories in a free-ends beam or to structural concept of Michell’s beam.

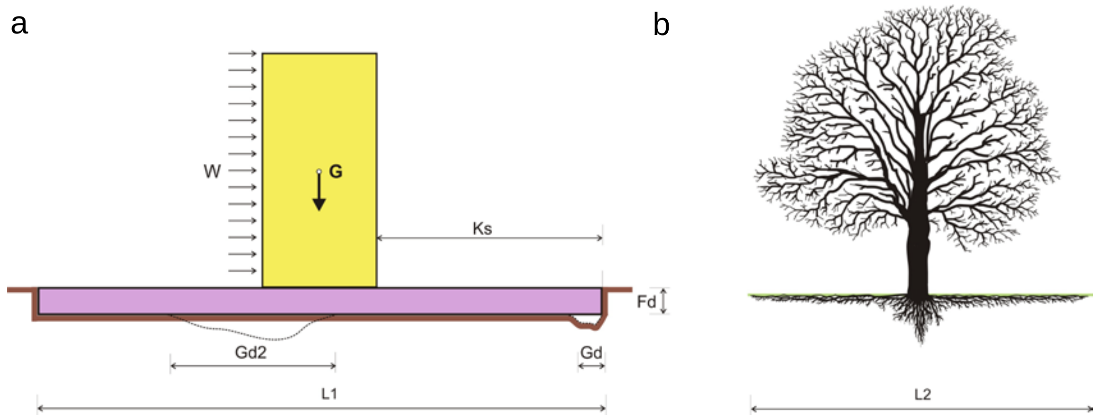


**Figure 1. Analytic scheme of vertical cross section of building having very large form of shallow foundation and similar scheme of tree structure together with its root system**

Shape of the root system of certain kind of a deciduous tree, see Fig. 1b, was one of inspirations in the design process of the proposed structural system of foundation, which could obtain the above defined features. The own weight of a tree is transmitted through its trunk to extensive root system composed of numerous small components distributed quite uniformly and shallowly in the subsoil.

## Structural concept of proposed foundation

Heavily loaded object can be mostly located safely on subsoil of very small load capacity if its shallow foundation will have big enough horizontal surface. It can be represented by an example and simple form of foundation structure, see Fig. 2, which consists of two beams (Bm) parallel to each other, located on a common horizontal slab (SLb), joined also by help of distanced elements (De) put in selected places of upper parts of beams, see Fig. 2d, [15]. The length of these beams should be considerably big (Ld). In this case the concentrated force (Fk) can be spread onto a suitable large surface. The point of the proposed technical solution is to arrange, in a narrow space between two main beams, an intermediate system (Int) of straight structural members connected together by means of structural nodes (Sn) being theoretically the articulated joints. Structural nodes (Sn) have to be not connected to the main beams. Outer concentrated force (Fk) is applied to upper node (A1) of a short vertical member situated between boundary nodes A1 and B1, which is put in vertical guides and having possibly of displacement only along the vertical direction.

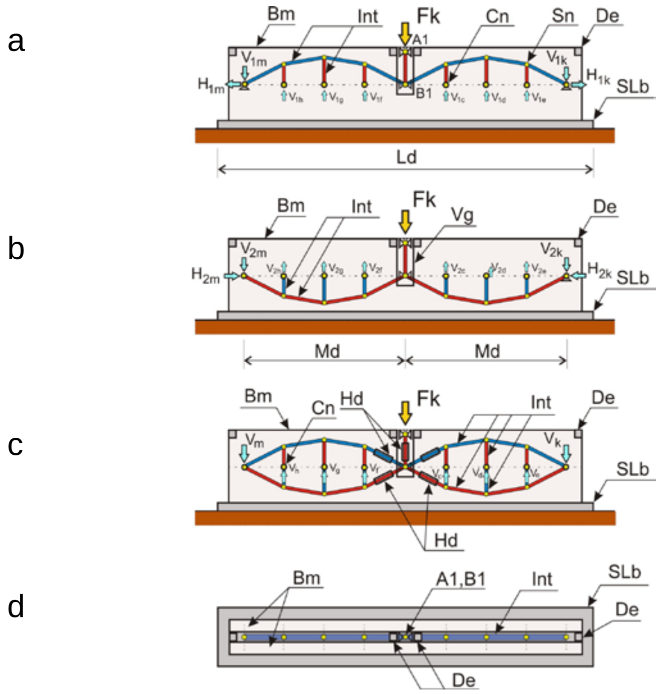


**Figure 2. General schemes of basic structural configurations of the system of combined foundation**

The intermediate system is built of two subsystems, while each of them is connected to lower node (B1) of the short vertical member. In this particular case the subsystems are composed of two parts arranged symmetrically towards vertical axis of central member put between nodes A1 and B1. The first one of these subsystems is called funicular system, see Fig. 2a, and it is built of struts placed along broken curves of convexity directed up. Structural nodes (Sn) of this subsystem are the upper nodes of short vertical members, lower nodes of which are the central nodes (Cn). In the boundary central nodes act, except vertical ($V_{1m}$, $V_{1k}$), also the horizontal components of reactions ($H_{1m}$, $H_{1k}$) and senses of the last vectors are directed outside the foundation. The central nodes are uniformly arranged along the neutral horizontal axis of the main beams, where deflections of bending beams are theoretically the smallest. Second subsystem is called an arch system, see Fig. 2b, its structure is similar to the first one but its pattern is symmetrical towards the neutral axis of horizontal beams. The main members are located along a broken curve of the convexity directed down. As previously structural nodes are connected by means of short vertical members to the central nodes. In this case in the boundary nodes act horizontal components of reactions ($H_{2m}$, $H_{2k}$) of the same values like reactions $H_{1m}$ and $H_{1k}$ but they are directed oppositely, it means towards center of the foundation. When these both subsystems are combined together, see Fig. 2c, then in the boundary central nodes act only vertical components of reactions ($V_m$, $V_k$), which in this case are directed down. The distance between node B1 and the boundary central nodes can be considered as structural module (Md) of system of the combined foundation. The final form of the intermediate system takes a lenticular shape, due to which it has some inherent features of damping of energy of vibrations evoked by dynamic load. This ability can be significantly increased e.g. by arrangement of computer controlled hydraulic jacks (Hd) in selected members of the intermediate system as well as in the main vertical member situated between nodes A1 and B1. The hydraulic jacks will be integral parts of structures of suitable members. The main beams and horizontal slab will be made as concrete or reinforced concrete structures. Component parts of the intermediate system can be made as steel members, as well as the reinforced concrete structures or certain types of composite materials of very high strength. Proposed structural system of foundation has been patented [16].

The proposed system of combined foundation can be shaped in various ways, see Fig. 3. Members of the intermediate system can be arranged on both sides of a single beam, see Fig. 3c, what implies that appropriate pairs of central nodes have to be joined by bolts interpenetrating matter of the beam (Bm), due to which the reaction forces are applied theoretically in the middle points inside space of the beam. Single segments of the intermediate system, having modular length (Md), can be repeated many times along the horizontal direction. Adjacent segments have to be connected by help of special type of central nodes B1 or Cx, which are also not connected to matter of the beam and have freedom of dislocation along vertical plane. Number of replications of single segments of intermediate system is optional what implies, that foundation structure designed in the proposed way may obtain extremely large length or surface, which theoretically can be unlimited.

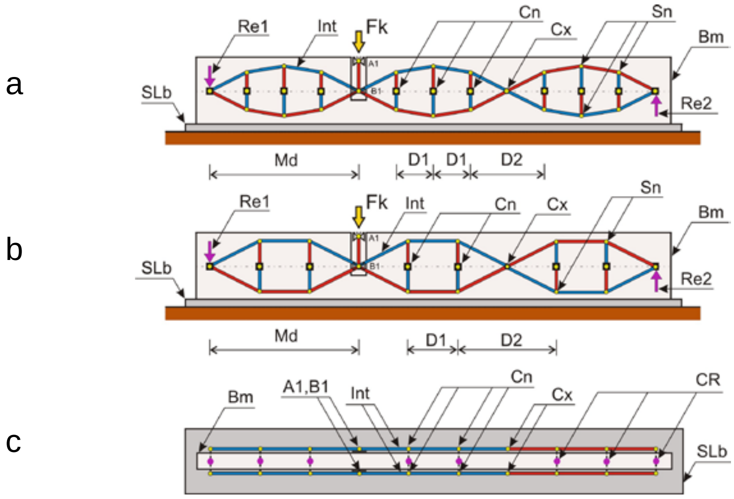


**Figure 3. Simplified schemes of arrangement of components of intermediate system around single shape of the main beam**

Vectors of reactions acting in boundary central nodes (Re1, Re2), depending on mutual structural configuration and number of replication of these modular units, can be of various senses. The outer concentrated force (Fk) can be apply at any part of the foundation but always according to structural requirements described previously. Regular geometric subdivision of single modular unit does not ensure uniform distribution of vertical components of reactions appearing in the central nodes. However distances between these nodes within single modules are of the same length (D1) but distances between two central nodes in two adjacent modules (D2) are twice bigger. The main structural goal of proposed system of the combined foundation is to distribute the concentrated load force (Fk) to numerous central nodes (Cn) uniformly arranged along neutral axes of horizontal beams, where vertical reactions can be of smaller values and will be applied to points (CR) located in the middle plane of a beam, see Fig. 3c. When number of central nodes located within a single module (Md) is big, then values of these reactions can be significantly smaller. But on the other hand the shape of the foundation structure is complex what causes, that useful advantages of its inner space are considerably restricted. Therefore it is proposed to reduce the number of central nodes only to two, which are situated within the structural module, see Fig. 3b, as well as to slightly modify geometry of components of the intermediate system. The point of the modification is to unify sizes distances (Dn) between central nodes, see Fig. 4a, what is presented on example of foundation, see Fig. 4b, built by means of single beam (Bm) put on slab (SLb). Members of the intermediate system are connected together in suitable nodes at the right angle or at angle of 45 degrees. Due to this recommended geometry the necessary technical or technological openings inside the main beams can be relatively big. Alternately directed senses of vectors of the vertical reaction forces acting in some adjacent pairs of central nodes cause, that the main beams (Bm) have to be of appropriate big stiffness because they are subjected to big values of bending moments and shear forces acting along the vertical surface. Construction depth of beams will be equal to one or to a set of typical floors.

a

b

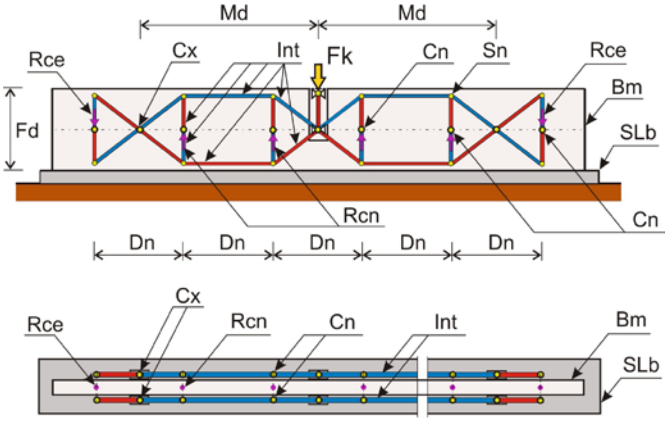


**Figure 4. Recommended geometry of components inside space of proposed structural system of foundation**

One should strive to distribute the main load in form of concentrated force (Fk) along at least two various horizontal directions, what ensures significant decreasing the values of reactions applied in the central nodes of the large horizontal surface of the combined foundation shaped like a specific type of foundation framework. Figure 5 shows scheme of structural module of such foundation formed around selected part of single beam having modular length (Md) and construction depth (Fd). This modular part of beam has suitable cut-outs located in the middle of vertical edges, where in the free spaces are located boundary nodes of single segments of the intermediate system (Int) arranged symmetrically around both vertical sides of the main beam. When the structural module, consisting of a beam and intermediate system, will be situated in perimeter zone of the foundation structure then its outer side have to be protected from the adjacent ground by help of additional border wall put vertically in relatively short distance to the main matter of beam.

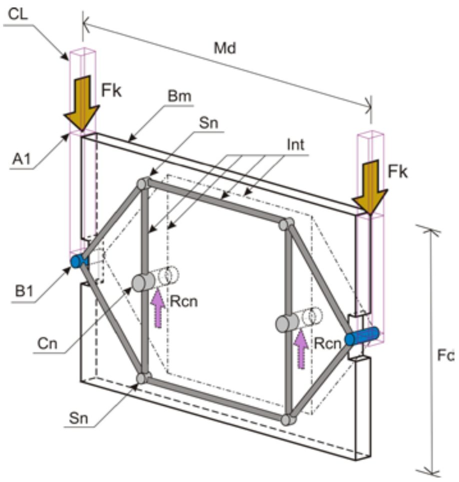


**Figure 5. Example of shape of structural unit of proposed type of foundation**

Such structural units can be component parts of the foundation frameworks having patterns of rectangular, triangular or other type of a grid. Figure 6a shows an exemplary shape of set of four structural modules creating spatial module of square grid of foundation framework. Modular segments of the main beams (Bm) should be connected together by means of e.g. rigid joints (Rjt), which can be made in various ways. Lower parts of shorts struts placed between nodes A1 and B1 are connected to the middle parts (Mp) of nodes of the type B1 placed in spaces of suitable cut-outs (Bx). Geometric dimensions of this spatial foundation module, measured along horizontal directions, can be in the real structure quite big as well as the value of its construction depth (Fd) what implies, that its inner space has to be supplemented by some additional structural members. Figure 6b shows simplified scheme of such foundation module containing certain number of vertical columns (Col) located inside the space of a structural box, which columns are intermediate supports for slabs (FL) of the inner floors. In each vertical side wall (Bm) can be arranged appropriate and large technical openings (Op), presence of which makes possible to design the inner spaces of the foundation for numerous useful purposes of the building.

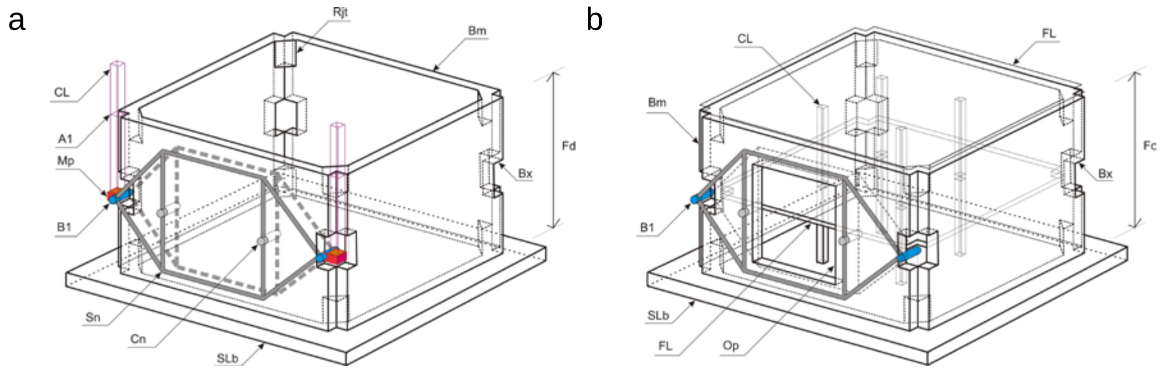


**Figure 6. Views of simple forms of spatial structural module of system of combined foundation**

Structural system of the combined foundation makes possible to spread the matter of shallow foundation on the large horizontal surface by keeping the basic rules of theory of structure. It can be also a stabile support for objects even after large displacement of subsoil beneath the foundation structure. Therefore, this shape of technical solution can be consider as satisfactory solution of the research problem defined previously. However, the structural system can be considered as somewhat complex but it enables to construct the safe buildings in areas of very difficult or dangerous environmental conditions.

## Proposal of application

System of combined foundation can take various forms and it fulfils the main structural conditions required from foundation of buildings located in the earthquake areas defined at the beginning of this research. The main body of this foundation can be of very big length or large surface, Fig. 7a, and it can be horizontally separated (Hrs) from the background.

Proposed type of combined foundation, due to its very large surface, can ensure stability to the whole object even after dynamic dislocations of big parts of the ground. In selected members of the intermediate system (Int) one can put the electronic controlled hydraulic jacks (Hd), what will considerably increase the inherent ability of damping vibrations, which is characteristics for this structural form. Because to the boundary nodes (Ce) are applied vertical reactions directed down therefore, it is proposed to locate below these nodes additional foundation plies (Fp) in order to stabilize this part of structure.

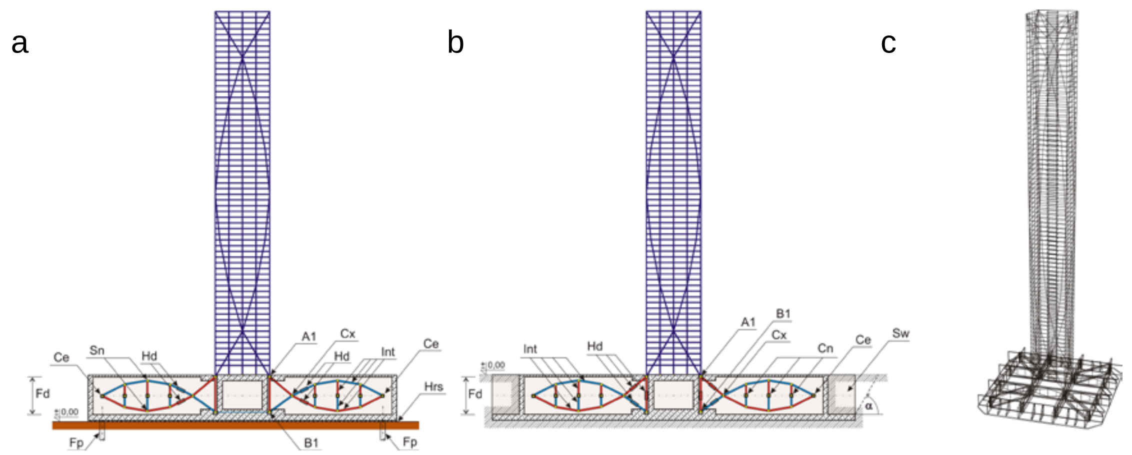


**Figure 7. Schemes of combined structural system of tall building located on proposed type of combined foundation**

Another way of stabilization of these parts is to shape there a type of big scoop, see Fig. 7b, where the weight of ground located in the soil wedge (Sw), determined by angle of slide (α), will play similar role like the foundation plie. When the multi-storey building is supported on the proposed type of foundation and inside its aboveground structure is applied suitable bracing in shape of the lenticular girder, then the whole bearing structure is called the combined structural system of the tall building. Figure 7c shows simplified scheme of structural system of tall building shaped in similar way, being a suitable visualization of numerical model of the system defined in programming language Formian [17]. Initial static analyses of this structural system have been done on basis of this numerical model by application of computer software Autodesk Robot Structural Analysis Professional 2016.

## Conclusions

The proposed structural system of combined foundation fulfils requirements defined at the beginning of the research task. Its horizontal surface is theoretically unlimited and it can be the safe and reliable foundation structure for the heavily loaded buildings, which have to be placed even on ground of very small load capacity or located in seismic area. Application of this structural system does not need to make deep foundation trenches, that is why its presence should not destroy the natural underground water system and it can be relatively inexpensive technical solution. However, it is somewhat complex structure but it will make possible the safe foundation of objects in areas, which nowadays are considered as difficult or almost impossible to use for building purposes. It is expected that specific form of system of combined foundation can be applied to straighten the previously inclined objects. The proposed structural solution of combined foundation has to be subjected to numerous and complex structural, static and dynamic analyses and also to research tests in order to verify all the assumptions and expectations.

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